APOLLO

Final Report

CONFIDENTIAL

ER 12008–1 JUNE 1961

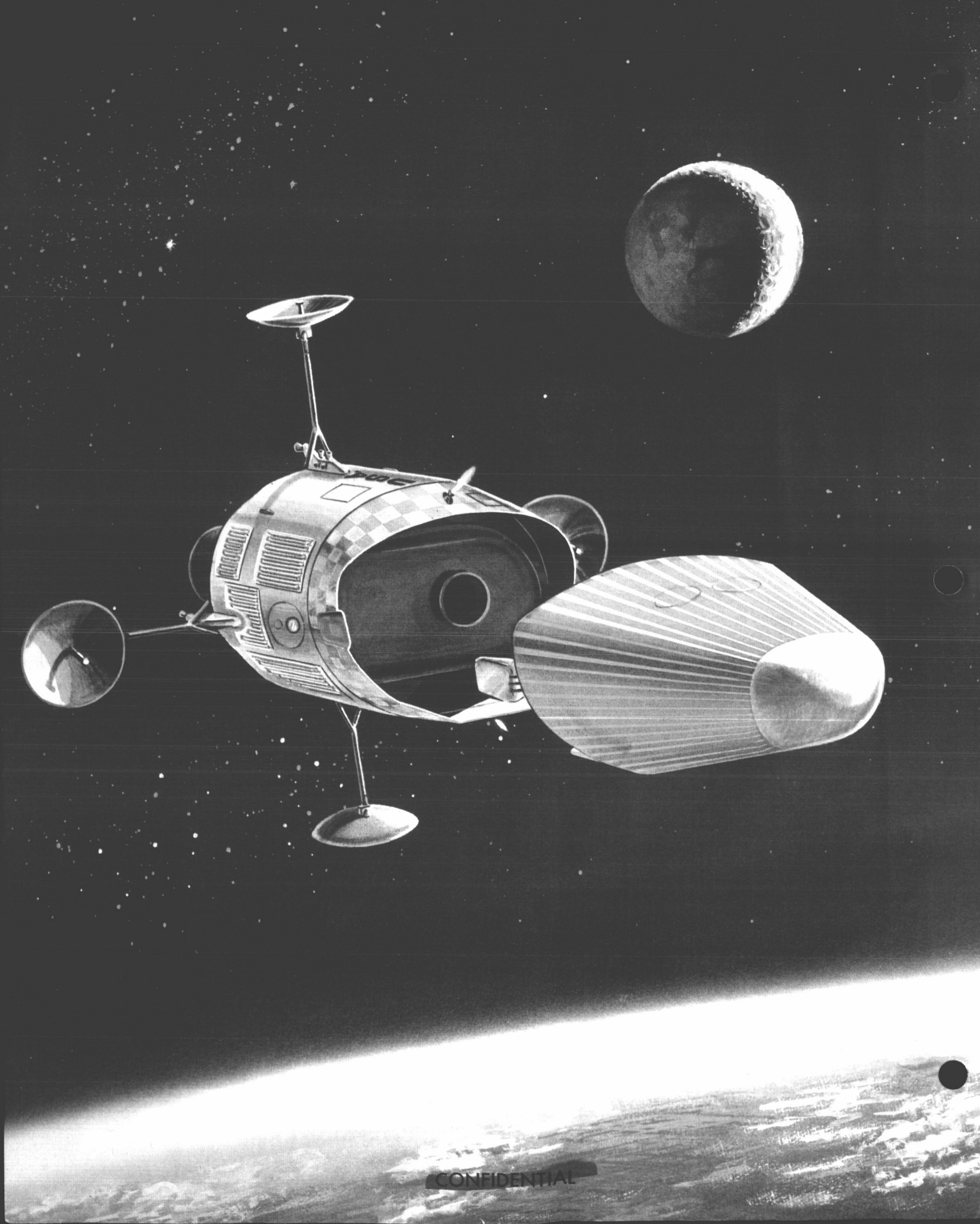
~~Available to NASA Offices and~~
~~NASA Centers Only~~

Life Sciences I

EXCLUDED FROM THE GDS

MARTIN

CONFIDENTIAL



CONFIDENTIAL

CONFIDENTIAL

APOLLO

Final Report

Submitted to: NASA Space Task Group.
Contract NAS 5-303, Exhibit A, Item 1.2

Life Sciences I

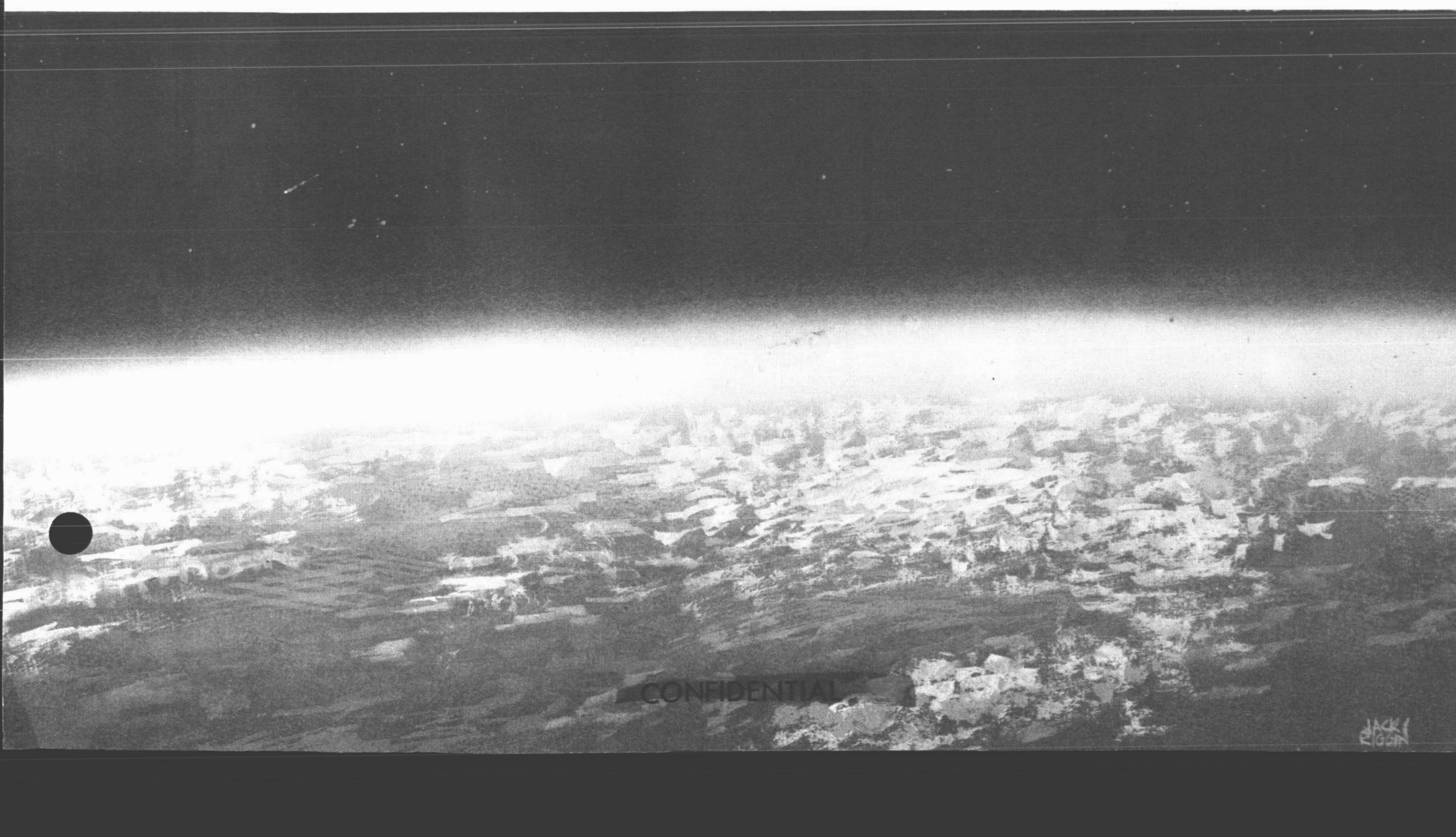
THE FUNCTIONS AND CONTRIBUTIONS OF MAN IN THE APOLLO SYSTEM

ER 12008–1 JUNE 1961

CONFIDENTIAL

MARTIN

EXCLUDED FROM THE GDS



CONFIDENTIAL

MODEL 410 — THE SYSTEM AND ITS OPERATION

*A BRIEF DESCRIPTION**

Model 410 is the spacecraft system recommended by Martin for the Apollo mission. Its design satisfies the guidelines stated in NASA RFP–302, as well as a more detailed set of guidelines developed by Martin during the Apollo design feasibility study.

We conceive the ultimate Apollo mission to be a manned journey to the lunar surface, arrived at by the preliminary steps of earth orbit, circumlunar and lunar orbit flights. Operational procedures proved out in the early steps will be carried over into the advanced steps, thus establishing a high level of confidence in the success of the lunar flights. With the recommended system, manned lunar orbit missions can be made as early as 1966.

Operational Features

For a circumlunar flight when the moon is at its most southerly declination (Fig. p–1) the launch operation proceeds southeast from Cape Canaveral and down the Atlantic Missile Range. The Saturn C–2 third stage shuts down when orbital velocity is reached at an altitude of 650,000 feet. What follows is a coasting orbit passing over the southern tip of Africa, the Indian Ocean and up the Pacific Missile Range. In this interval the crew checks out all onboard equipment, which has just passed through the accelerations, noise and vibration of the boost phase. If the pilot-commander is satisfied that all systems are working properly, the third stage is restarted and the spacecraft is injected at parabolic velocity northwest of Hawaii. If the pilot-commander is dissatisfied with the condition of the vehicle or crew, he separates from the Saturn S–IV, starts the mission abort engine, re-enters at the point shown in Fig. p–1 and lands at Edwards AFB.

Continuing translunar flight from the point of injection, the trajectory trace swings down over the Caribbean and then west over South America. This particular trajectory passes within 240 naut mi of the moon, then turns back for a direct re-entry some six days after launch. Re-entry occurs southwest of Hawaii some 3300 naut mi from the Edwards AFB landing site.

Tracking. The range coverage provided by present and planned facilities is shown in Fig. p–1 for this trajectory and for a second return trace representing the case when the moon is at the most northerly declination. This second trajectory establishes the 10000-naut mi re-entry range requirement for Apollo to meet the guidelines of operation on every day of the lunar month and of operation into a single landing site.

*For more complete descriptions, see ER 12000 or ER 12001.

Abort. During the critical launch and checkout phase, abort will be possible at any time : at the crew's discretion, automatically or by ground command. Up to nine minutes after launch (from Canaveral), the abort landing is restricted to the AMR for a circumlunar flight. Beyond this point the pilot has the option of continuing to any point along the AMR, PMR or into Edwards AFB through the use of the mission abort propulsion system and the inherent downrange maneuverability of the Model–410.

The Selected Spacecraft

The Apollo space vehicle (Model 410 spacecraft plus launching vehicle) is shown in Fig. p–2. The spacecraft—that portion of the space vehicle which makes the flight to the moon—consists of these three modules:

(1) Command module, housing the three crew members during all thrusting periods, e.g., launch from earth, any corrections to the flight path during flight in space, during re-entry and, ultimately, during landing and launch from the moon. It is the operating center from which all control of the flight is made.

(2) Propulsion and equipment module, containing all the propulsion units which operate between the point of final booster separation and re-entry after the lunar flight. It is separated from the command module at 200 naut mi from the earth on the return trip. It is designed with tankage for lunar takeoff and will be offloaded for less ambitious missions.

(3) Mission module—contained within the outer frame of the propulsion and equipment module—providing space during the lunar voyage for scientific observations and crew living functions.

Command Module

With its lifting capability, the Apollo command module represents a step forward in technology over ballistic vehicles, Mercury and (to the best of our knowledge the *Boctók* (*Vostok*). The lift results from the capsule's shape—a blunted cone flattened on the top (see Fig. p–3).

Heating and radiation protection. The Model 410 is shaped conservatively for aerodynamic heating in addition to its relatively high L/D (0.77). By accepting the large convective heat load of a nose radius smaller than that of the Mercury type, the Model 410 shape tends to minimize radiative heat transfer which is less well understood and harder to protect against. The thermal protection system provides excellent protection for the crew from the large aerodynamic heat loads, from space radiation (including solar flares) and from meteorites.

The normal mission radiation dose will not exceed the five rem limit defined by NASA. If the crew should encounter a solar event as severe as that following the May 10, 1959 flare, they would receive a dose of only 67 rem—well within the 100 rem dose limit set by Martin as tolerable during an emergency.

Thermal protection for re-entry is provided by a composite shield of deep charring ablator (nylon phenolic) bonded to superalloy honeycomb panels which are set off and insulated from the water-cooled pressure shell. The control flaps are protected from the high initial heat rate by an ablator bonded directly to the flap. The long-time, lower heating rates are handled by re-radiation from the backside. The aft bulkhead is protected by a fiberglas phenolic honeycomb panel with a foamed polyurethane insulation.

Crew provisions. The crew has access to all electronic and electrical equipment in the command module for maintenance and replacement. Both pilots have two-axis sidestick and foot controllers as well as a manual guidance mode used with the computers inoperative for deep space and re-entry operations.

Cabin pressure is maintained at the equivalent of 5000 feet altitude ("shirt sleeve" environment). Protective suiting is donned only for launching and landing, but need not be inflated except in emergency.

Guidance. The guidance system consists of both automatic and manual star tracking equipment, as well as two inertial platforms and two general purpose digital computers. Two windows, with ablative heat shield covers, are provided for use with tracking instruments.

Flight control. Pitch and yaw attitude control within the atmosphere is provided by flaps driven by hot gas servos. Outside the atmosphere dual reaction controls are used. Roll is controlled at all times by a dual reaction system.

Communications. Communications equipment includes a K_u band for re-entry, a C-band for the pre-reentry and both HF and VHF rescue beacons for landing and recovery.

Landing system. The landing system consists of a steerable parachute, retro-rocket combination, enabling the M–410 to avoid local obstacles, trim out wind drift and reduce sinking speed to a nominal three feet per second—low enough for safe landing on any kind of terrain or in very rough seas. In the event of retrorocket failure, accelerations on the crew will not exceed 20 G.

Launch escape propulsion system (LEPS). LEPS is a thrust-vector-controlled, solid rocket system which separates the command module from the rest of the space vehicle in the event of an emergency during launch pad operations or during boost through the atmosphere. In an off-the-pad abort, it lifts the command module to an altitude of more than 4000 feet. During a normal boost trajectory, LEPS is jettisoned at 300,000 feet.

Propulsion and Equipment Module

The propulsion and equipment module (shown in Fig. p–3) contains propulsion devices and equipment which are not necessary for re-entry. Its outer skin serves both as a load carrying structure and as a meteorite shield for the propellant tanks, mission module and other equipment.

Propulsion devices. The mission engine, used for trajectory correction and abort, is a high preformance, modified LR–115 (Pratt & Whitney), developing 15,600 pounds of thrust. A total of 10,450 pounds of liquid hydrogen and liquid oxygen propellants may be carried, sufficient for lunar takeoff.

Four vernier engines, with 300 pounds of thrust each, are used for mid-course correction, ullage impulse to settle the mission engine propellants and for thrust vector control during operation of the mission engine. In addition there are two sets of six control jets which provide 30 pounds of thrust for roll, pitch and yaw control.

Power sources. Spacecraft equipment is powered by fuel cells (2 kw) which under normal conditions, use the boiloff from the mission propulsion system. A supply of independent reactants is provided for emergencies. Battery power is used during re-entry.

Communications. Four large antennas fold out to provide S-band communications and X-band radar altimeter information. VHF communications gear is also provided.

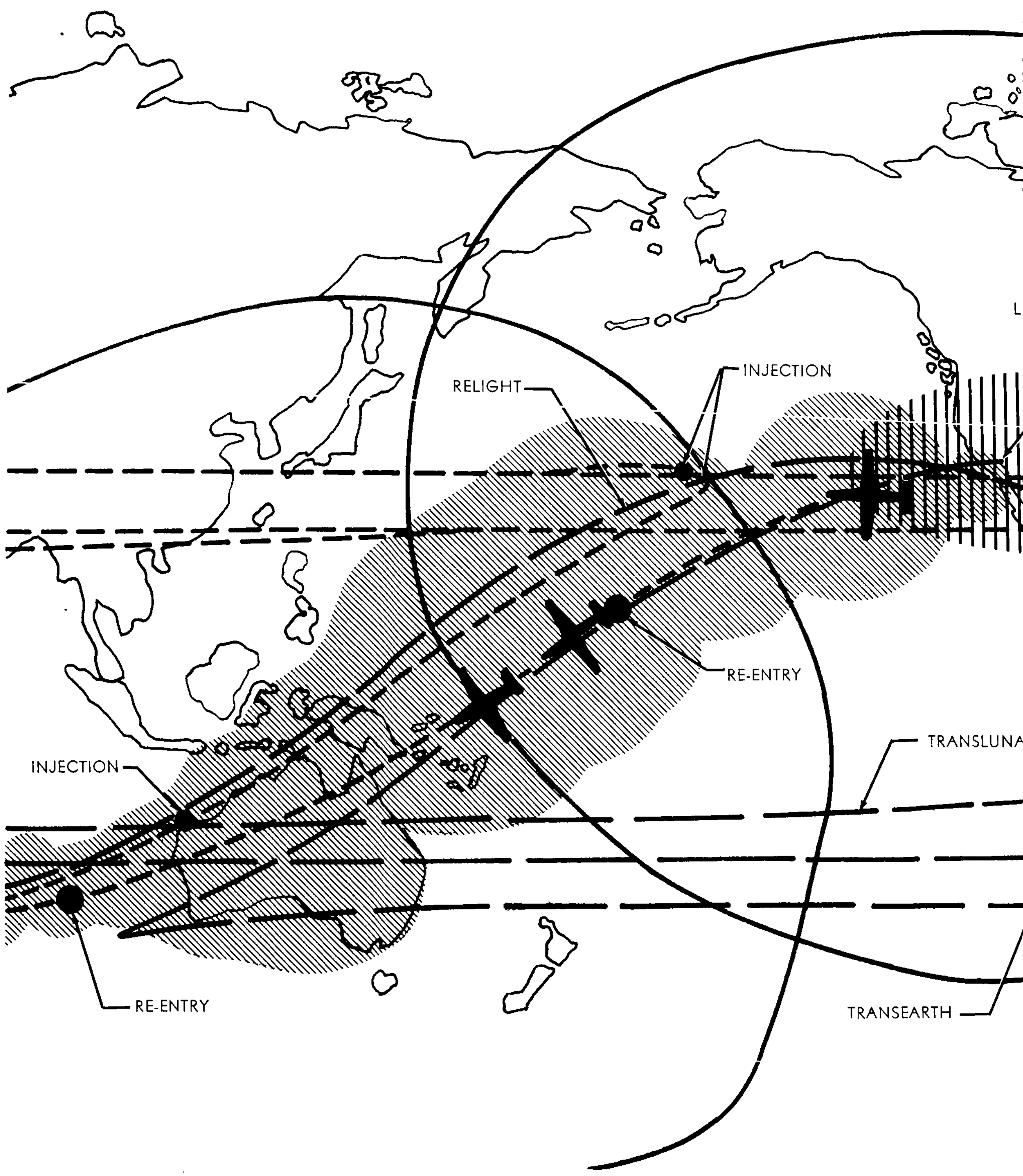
Mission Module

The mission module provides 400 cubic feet of living space during the lunar voyage. It serves as a midcourse work-rest area, providing freedom of movement and privacy. For operations on the lunar surface it will be a base of scientific investigations, and will serve as an airlock. The same "shirt sleeve" environment at 12.2 psi is maintained as in the command module.

The mission module provides the space and flexibility required for effective lunar reconnaissance and scientific experimentation. An Eastman-Kodak camera-telescope has been selected, for example, which has one-meter resolution at lunar orbit altitude of 50 naut mi.

MODEL 410 WEIGHT SUMMARY

Mission	Circumlunar	Lunar Orbit	Lunar Takeoff
Command Module	6954	6954	6954
Propulsion and Equipment Module	7372	13,192	15,618
Launch Escape Propulsion System	185	185	0
Adapter	489	489	0
Effective Launch Weight	15,000	20,820	22,572



INJECTION
RELIGHT
RE-ENTRY
TRANSLUNA
INJECTION
RE-ENTRY
TRANSEARTH

[redacted]

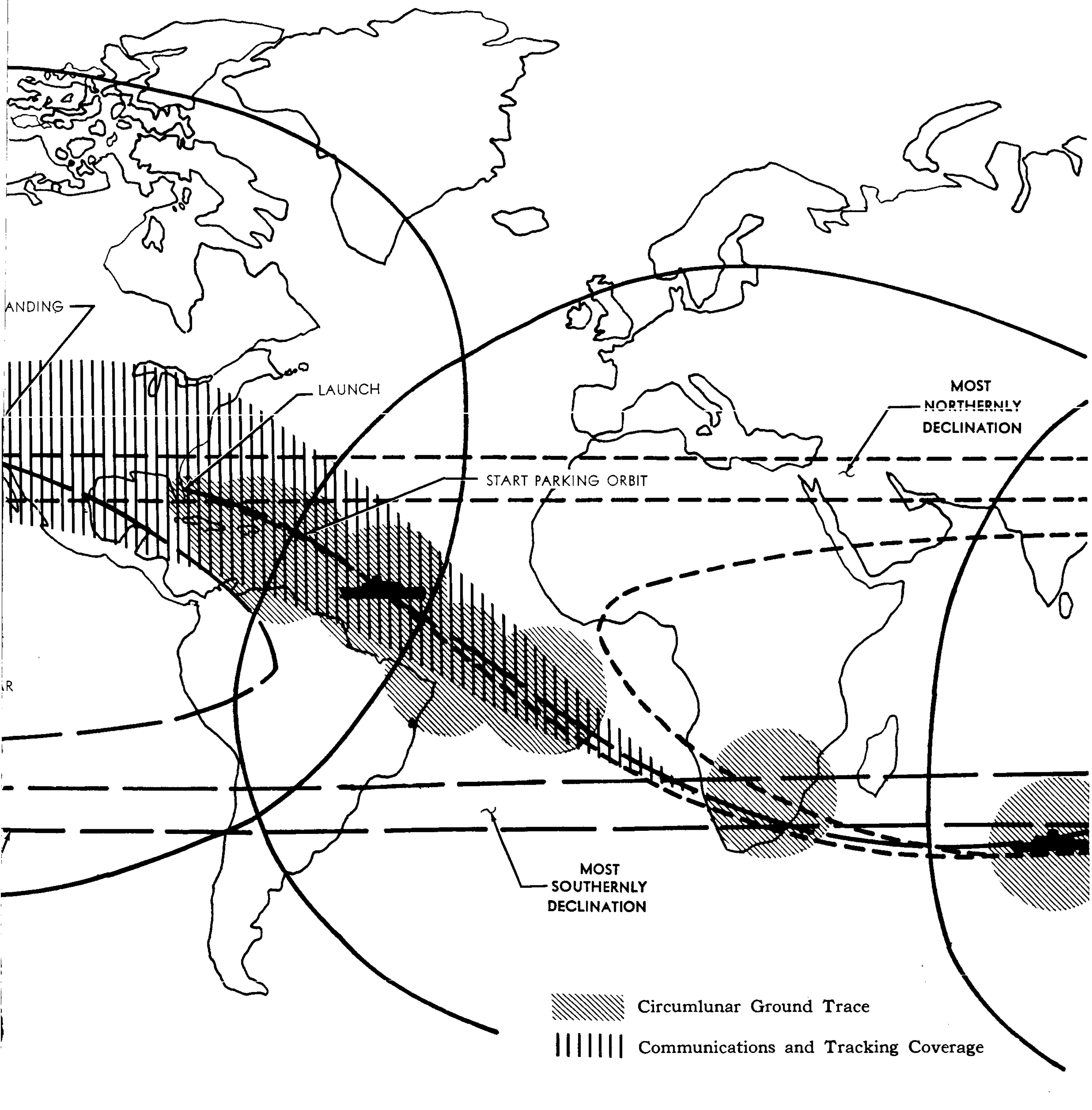
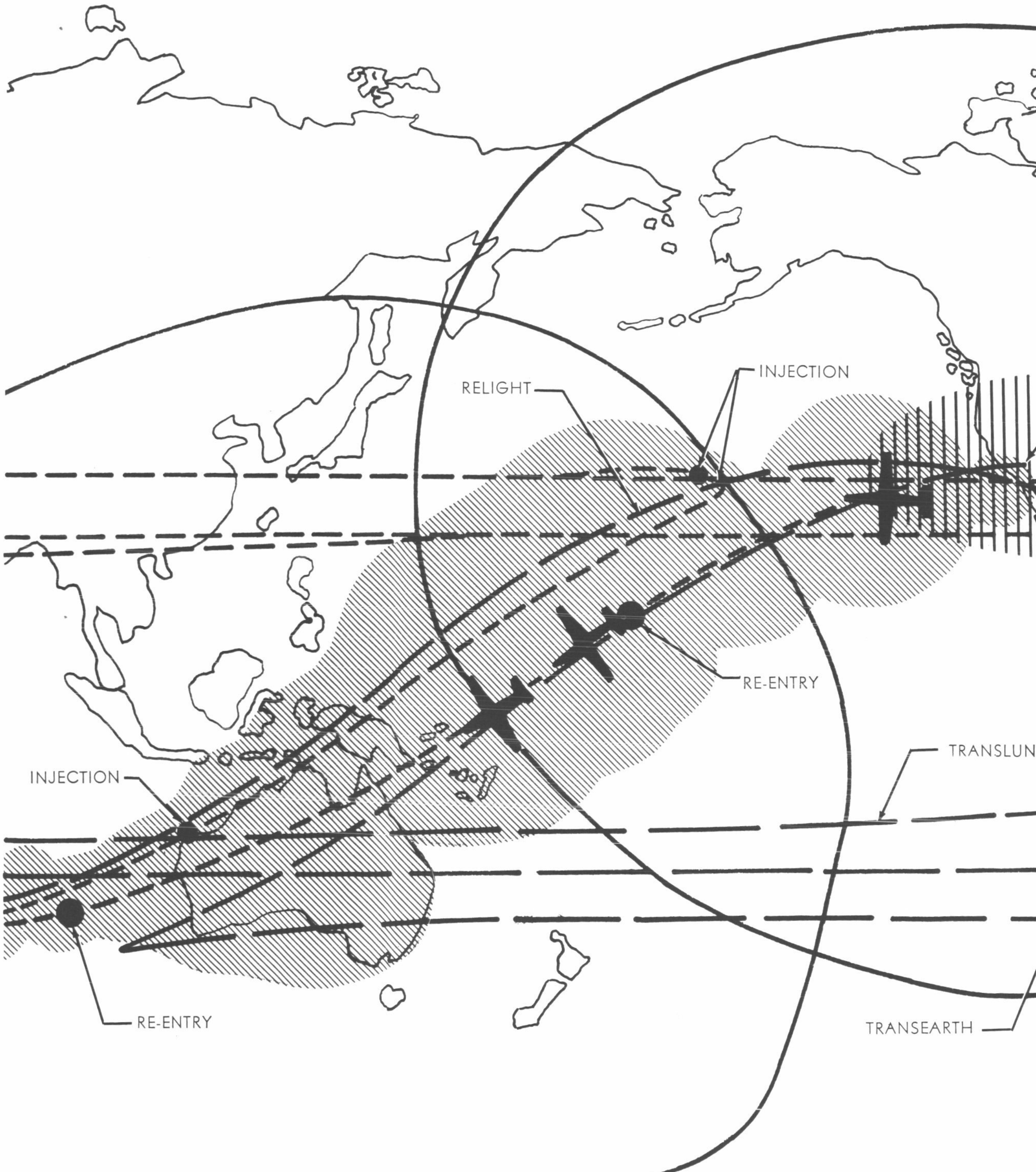


Fig. p–1 Model 410 Circumlunar Trajectory and Range Coverage

[redacted]



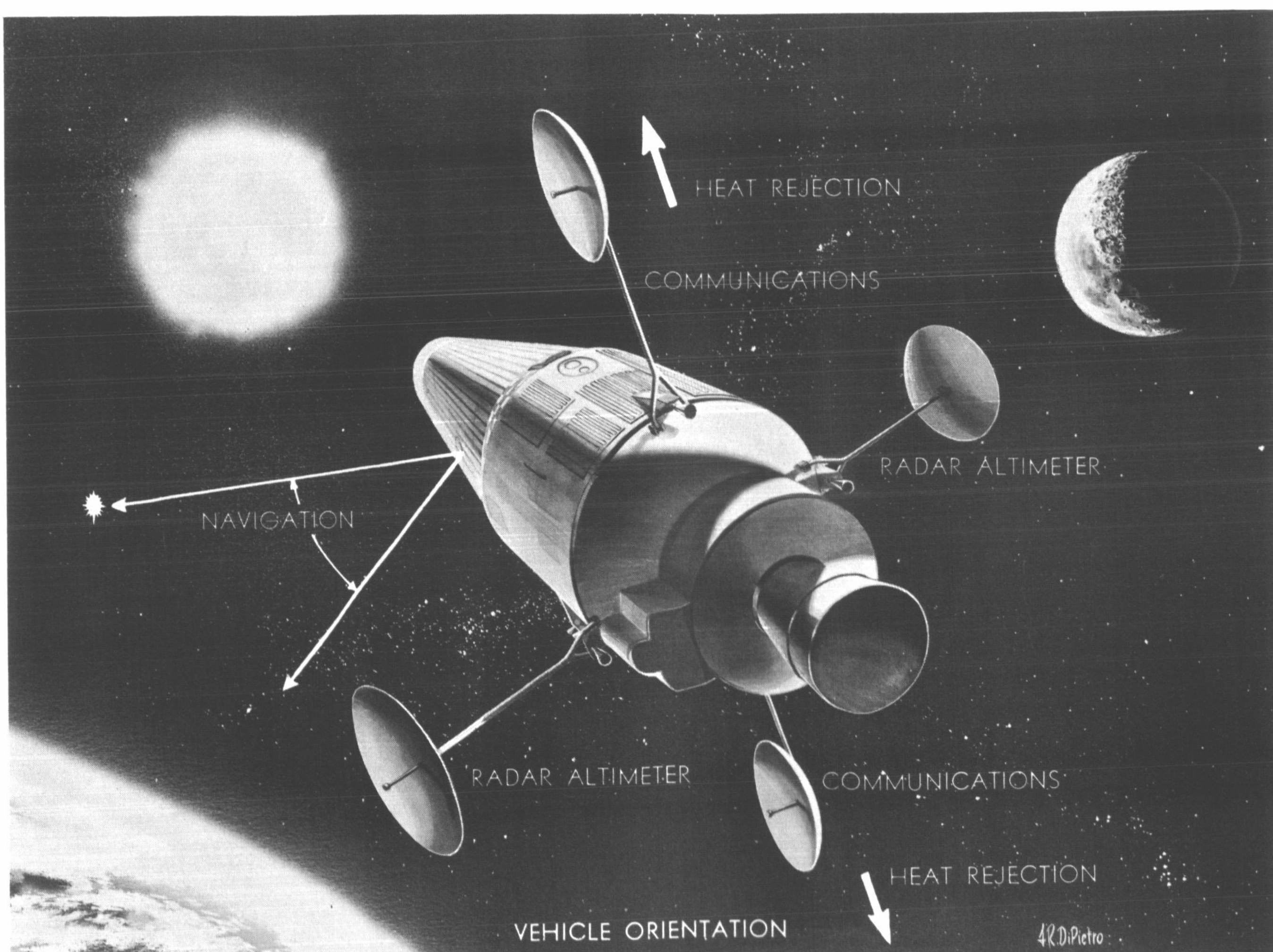
INJECTION
RELIGHT
RE-ENTRY
TRANSLUNA
INJECTION
RE-ENTRY
TRANSEARTH

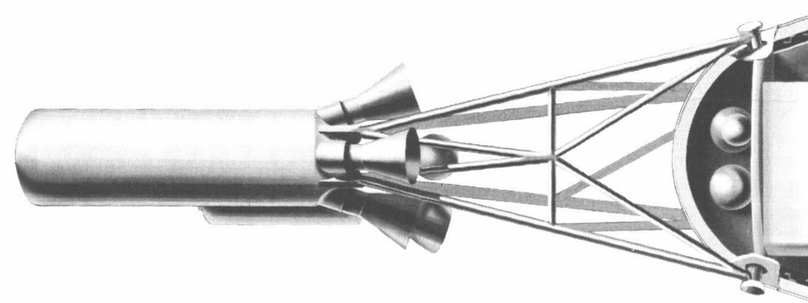
MISSION	EFFECTIVE GROSS WEIGHT (lb)	PROPULSION ΔV CAPABILITY (fps)	
		MISSION	VERNIER
CIRCUMLUNAR	15000	1830	525
LUNAR ORBIT	20820	6100	525
LUNAR TAKEOFF	22572	8600	200

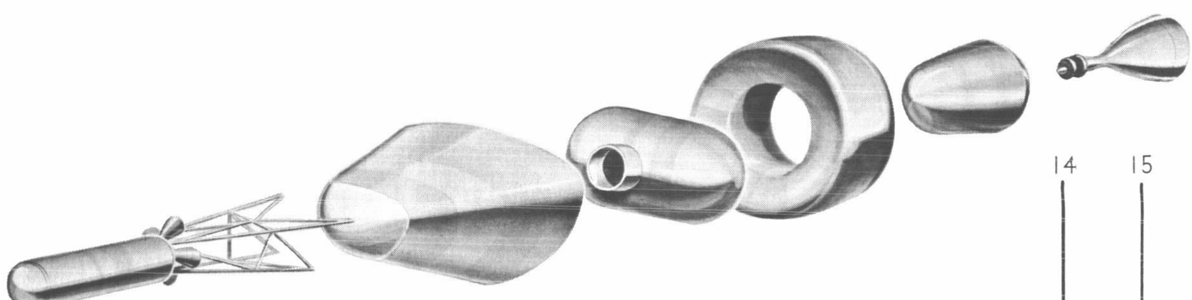
VOLUMES (cu ft)	
COMMAND MODULE	350
MISSION MODULE	400
MISSION H_2 TANK	400
MISSION O_2 TANK	122

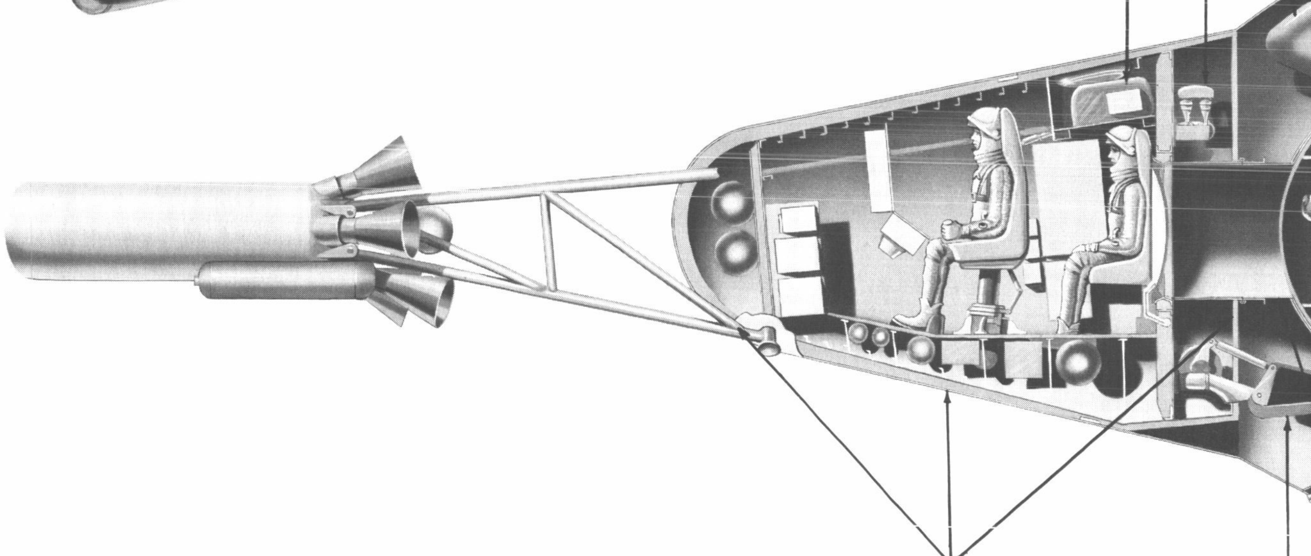
PROPULSION SYSTEM DATA

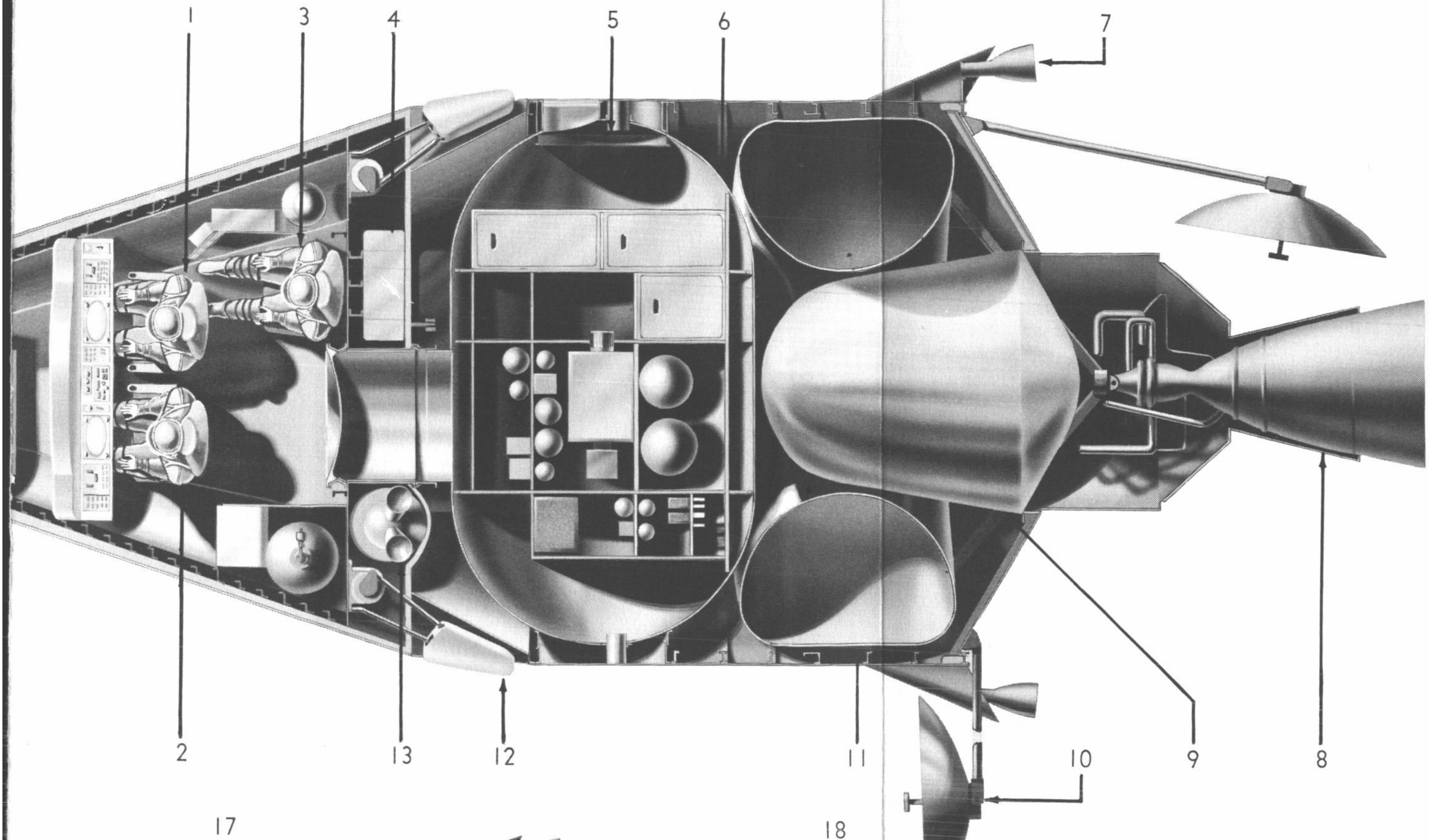
PURPOSE	TYPE	ISP. (SEC)	THRUST (lb)
MISSION (1)	H_2—O_2 (ADV. LR115)	427	15600
VERNIER (4)	N_2H_4/UDMH–N_2O_4	315	300 EACH
ATTITUDE CONTROL (14+BACKUP)	N_2H_4/UDMH–N_2O_4	250–315	15 TO 50

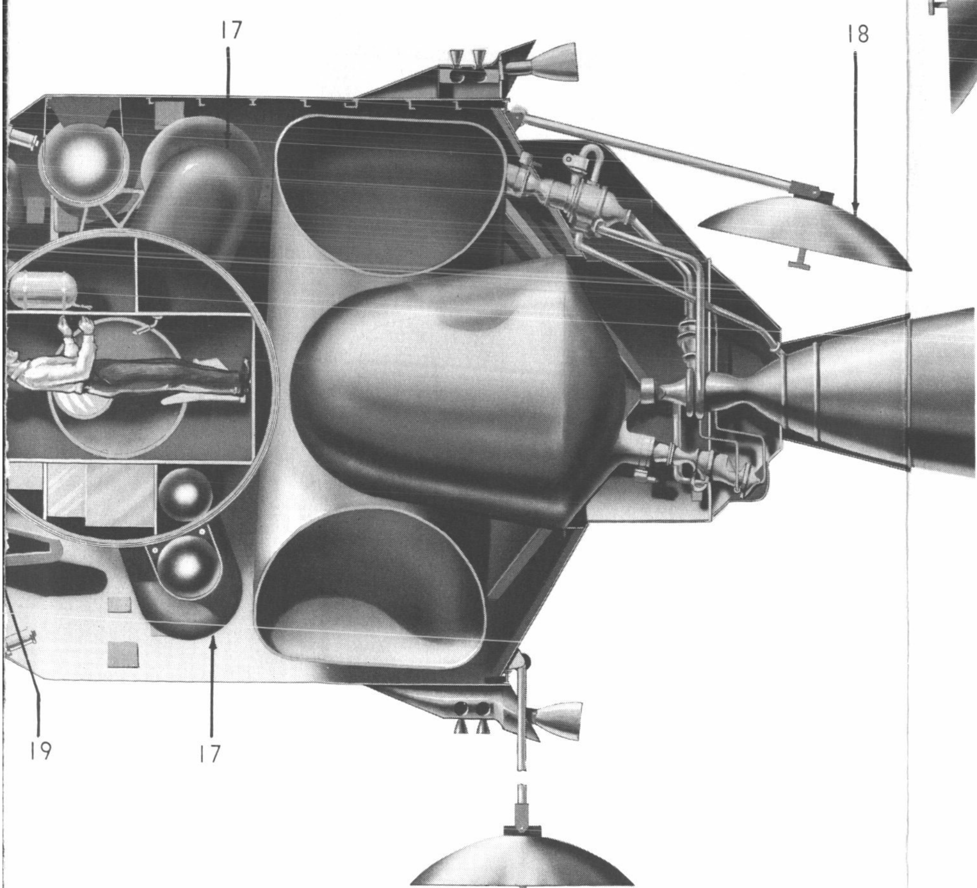







14
15
16
20
12





KEY

1. PILOT-COMMANDER
2. NAVIGATOR-PILOT
3. ENGINEER-SCIENTIST
4. MAIN CHUTES
5. MAIN HATCH
6. MISSION MODULE
7. VERNIER ENGINE
8. MISSION ENGINE
9. OXIDIZER TANK (LOX)
10. S-BAND PARABOLIC ANTENNA
11. TOROIDAL FUEL TANK (LH)
12. FLAPS
13. RETROROCKET
14. ASTRO-INERTIAL PLATFORM
15. ATTITUDE NOZZLES
16. FUEL CELLS
17. VERNIER PROPELLANT TANK
18. ALTIMETER ANTENNA
19. INTER-MODULE PASSAGE
20. HEAT SHIELD

Fig. p-3. Model 410 Apollo Inboard Profile

CONTENTS

SUMMARY

This report concerns man in the system. A brief analysis of known human capabilities is presented in three general areas: information processing, decision-making and control and tracking. It was concluded after performing this analysis that the major factors in the utilization of these human capabilities were providing adequate information to the crew and providing adequate modes of crew response.

The next set of analyses presented concerns the tasks and functions of the crew within the Apollo while two methods of analysis were performed, a sequential activities analysis and a time line task analysis. The results of these studies indicated the involvement and role of man within the system. Of particular importance was an inflight systems checkout procedure which would allow a decision to be made by the crew to continue to the next mission phase or to abort, dependent on the status of the system. A workload analysis was also performed, demonstrating the need for a three-man crew.

Based on the analysis of crew functions in the system, man's contributions to the system were quantitatively examined. Man contributes to the system in terms of increasing reliability, maintenance, mission effectiveness and as an emergency source of power.

The last chapter presents the spacecraft description. This included a complete description of the displays and controls, crew stations and an analysis of communication links within the system. The display system presented is compatible with the information needed by the crew to perform their assigned functions.

This report , then, presents the functional integration of the crew into the Apollo system. The spacecraft design and arrangement appears adequate for sustaining the crew and for allowing the crew to perform for a 14-day mission in terms of crew tasks and functions.

I. INTRODUCTION AND CRITICAL PROBLEMS

The studies reported here concern the integration of men within the Apollo system. Consideration has been given to men's role with the entire system. Our basic approach at the onset of the study was predicated on three questions. First, what are the design requirements for life support of the man in the system? Second, what are the tasks and functions which the crew of this system must perform? Third, what are the research programs and studies which must be performed to make this system feasible? Each of these questions has been answered in detail by analytical and empirical studies. The results of these studies have shown that man and his support are not the limiting factors in the feasibility of the Apollo system. Although there are problems and unanswerable questions concerning man in the system, research and study are either underway or planned to provide the required data. Research which is not underway at present can be immediately started because the techniques required are available.

Two physiological stress problems received considerable attention during this study. They were weightlessness and radiation. These problems were considered of utmost importance because they influence the total design of the system and its weight. They also could compromise the effectiveness of the crew. The results of these studies using the available data and analytical techniques have suggested these stresses can be handled within the system requirements of Apollo.

Another question which we were concerned with was the justification of crew size and function. We conducted numerous analyses concerned with crew function, crew workload, and the division of crew duties within the Apollo system. Based on these analyses and consideration of the best work rest cycles for a hypothesized 14-day mission, we believe a three-man crew can be justified. Once the size of the crew and their functions had been determined the requirements for the design of a display and control system were undertaken. A further design requirement of the display and control system was its incorporation into the operational concept of the system. The display and control system presented in this report is compatible with the crew requirements for information and control response, with the operational concept of the system and with the design of the spacecraft.

An investigation of which research and development programs should be conducted prior to and during Apollo missions yielded interesting results. Dependent upon the time span of the Apollo program, enough information could be obtained from already planned studies and early Apollo missions to substantiate the design of the system for human occupancy for a lunar landing in 1967. A great deal of effort was expended in a related direction; the mission of the Apollo system. This included consideration of biological and behavioral experimental orbital missions and the scientific mission during lunar orbit and the ultimate landing. The total results of these studies will be discussed in some detail.

In the course of conducting these studies, we found that man's contribution to the Apollo system could be quantified. Since we were initially concerned with a manned vehicle, our approach was not to justify man but merely to use him as efficiently as possible. This efficient use of the crew showed contributions to the system in a number of vital areas. These will be discussed in detail.

Certain problems were also amendable to experimental analysis during the study period. The studies conducted in this area were concerned with man's ability to perform the tasks required for the mission. These tasks were maintenance, decision making, visual detection, landing, midcourse corrections and rendezvous. We also investigated the stability of the operator's performance as a function of work time. Each of these studies will be reported in detail.

The last general problem area which was studied during this period was concerned with pilot evaluation. It was believed that a group of individuals from the same population from which the crew will be chosen should systematically analyze the system and the pilot's role. To aid in this evaluation mockups were constructed to functionally evaluate the displays and the internal arrangement of the spacecraft.

We have briefly described the studies conducted. The succeeding reports will present the pertinent data and results. This report has been organized as follows:

<u>ER 12008-1--Man in the System.</u> This report will discuss man's role in the system, the functions he will perform, his contribution to the system, the displays provided and the internal arrangement.

<u>ER 12008-2--Life Science Considerations.</u> This report will discuss the life science design requirements for both physiological and psychological factors. This report also discusses training and consideration of ground support equipment personnel. A set of design specifications for the life science area are also included.

<u>ER 12008-3--Research and Development Studies.</u> This report presents the research, development, mockup and evaluation studies conducted during the study period. Also included in this report are recommended Apollo preflight and inflight research studies.

<u>ER 12008-4--Conclusions and Recommendations.</u> This report contains the conclusions and recommendations of the life science studies.

<u>ER 12008-5--Figures.</u> All figures to be included in the Life Science Report are included in this report.

Aiding in the determination of crew functions and the display system were Minneapolis-Honeywell and The B. F. Goodrich Company. International Latex assisted in determining pressure suit requirements.

II. CONTRIBUTION AND UTILIZATION OF MAN IN APOLLO

The incorporation of man into any space system presents difficult problems in the engineering design of the system due to the need for designing for his safety and support. This is particularly true when weight considerations and booster availability are factored in. One can argue to some extent that an automatic system can perform some of the functions man would perform in space. However, it is apparent to one interested in the man versus machine argument that the machine or automated equipment is never rated higher than the man in the following areas:

(1) Decision making

(2) Information processing

(3) Tracking behavior.

The above statement becomes more evident if one considers the level of performance required in each of the above areas. Simple decisions, information processing, or tracking behavior may be done quicker by a machine but not at the same level of performance. Any machine can perform a function for which it was built or was programmed to perform. However, this same machine cannot take data which is not predictable and make decision responses. That is, the machine cannot generalize to different classes of data. This becomes particularly important in manned space system such as Apollo where all mission eventualities cannot be preprogrammed.

The problem of demonstrating what man can contribute to an advanced system such as Apollo is not difficult as it may appear. The difficulty, if any, arises not from the choice of what he is to contribute per se, but from the difficulty in determining methodologies to evaluate and quantify man's contribution. Further, the data available on human capabilities is somewhat limited in a quantative sense. Most individuals consider themselves authorities on the human capabilities and because of these personal biases reject or fail to reject data on the frailties or attributes of man on the bases of personal experiences. The approach which we have used has been that of the impartial scientist operating with data on a statistical bases. This has been necessary because of one important factor which pervades all biological organisms, particularly the human. This factor is called individual differences. This factor is the most important argument against personal experience because it is first empirically defined and secondly demonstrates itself in all aspects of the biological organism. Any biological organism differs from any other organism on a statistical basis unless it has exactly the same genetic inheritance and post partum experiences. The statistical basis on which these differences occur are usually considered to be normally distributed. These same statistical differences are also found in the sizes, shapes and functional capabilities of internal organs. More subtile intellectual differences in human capabilities exist in learning ability, in response ability and in general intelligence. Consideration of these factors then suggests that the only possible means of discussing man's capability is in terms of a majority of individuals presenting these traits.

Any analysis attempting to demonstrate the contributions of man to a machine system are based on a set of assumptions. The validity of these assumptions are ultimately dependent, in the present situation, on the operational performance of the Apollo crew. However, prior to this type of verification certain other criteria or assumptions may be used. These assumptions must have some logic and relatedness to the system. Laboratory data may be utilized in this manner dependent upon the degree of relatedness of laboratory conditions to actual system conditions or situations. The criterion utilized in determining the role man will play in Apollo and to some extent a justification of his inclusion are as follows:

(1) One of the major purposes of the Apollo system is to evaluate the role man can exercise in a space system. This would suggest that man should play a role in most of the subsystems in order to determine his precise limitations in the environment of space.

(2) Any inclusion or justification of man in the Apollo system must also be made on some estimate of utility he contributes to the system. Utility is usually expressed in terms of cost and weight. It may, however, also be expressed in terms of effectiveness of mission accomplishment or maintenance to assure reliability during mission time. This approach, is of course, more difficult but may represent the only reasonable means of assessing the value of man within the Apollo system. The assumptions of this approach and some of the results will be presented later in this section.

It, therefore, appears reasonable and logical to attempt to delineate the crew capabilities, functions and contributions to the Apollo system.

A. MAN'S CAPABILITIES

The capabilities of man which are to be presented are conceptualized in terms of the individual differences discussed above. Therefore, in each of the capabilities to be discussed a range or a set of limits will be presented. These limits are not only dependent on the statistical variance of the human but are also dependent on the situations used to obtain these data.

Our work has indicated that the capabilities of man which will be of the utmost importance for the Apollo system are as follows:

(1) Information processing

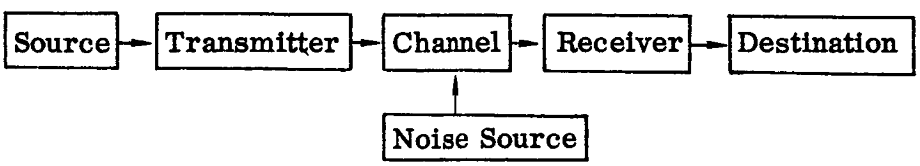
(2) Decision making

(3) Tracking and control behavior.

These three capabilities may be subdivided into many discrete functions which will be discussed in a later section. It should also be noted that information processing is a necessary pre-requisite to decision making and both information processing and decision making are necessary for tracking and control behavior.

1. Information Processing

In considering human information processing, it is a matter of convenience to conceptualize it in a manner similar to the transmission of information across a machine communication system. Therefore, the following sequence of events are applicable:



The noise source is based on the assumption that there is always some noise signal present. The only pertinent feature of noise is whether it would cause an alteration in the transmitted signal message. We, therefore, are only concerned with the probability that the noise signal changes. The unit of information transmission in which we will conceptualize man's performance is defined as a bit.

 [redacted]

Two additional concepts must be briefly introduced. The channel capacity of our system may be defined as follows:

$$\text{Channel capacity } C = \lim_{t \to \infty} C\ (T) = \lim_{t \to \infty} \log N\ (T) \qquad (1)$$

$$\frac{2}{T}$$

T = each signal of duration T; time units

C(T)= approximately the maximum number of bits that can be handled by the channel in one unit of time.

$\log_2 N(T)$= bits per signal of duration T time units if each N(T) signal were equally likely.

The entropy of the source or the distribution characterizing the source is defined as H. H is given as follows:

$$H = \sum_{i=1}^{n} p(i) \log_2 p(i) \text{ bits/selection} \qquad (2)$$

where:

p(i)= probability of the selection of symbol i from the given source.

$\log_2 p(i)$= transmission of bits of information from (S) of the symbol (i) which occurs with the probability of p(i).

The term entropy (H) will be used in the present context to represent the idea of amount of information transmitted or average uncertainty.

With these basic formulations stated, the capability of the human operator in information processing must be determined. Considering only the theoretical formulations of information theory, two estimates of human capacity are available. The first estimate considers channel capacity in terms of physical, physiological and pschological factors relevent to the transmission, the upper bounds of this channel capacity has resulted in approximately 10,000 bits per second. Another estimate of capacity is the consideration of varying certain variables and employing diverse coding schemes, the amount of information a human can be caused to handle suggests a lower bound of 10 to 100 bits per second. It should be noted that the lower bound, probably represents the limit of the human because of the inherent engineering difficulties in presenting noise-free information to the human operator and the lack of an adequate model for what functionally happens when a person processes information. Let us consider information processing of the human dependent on the sense organ stimulated.

(1) Hearing. Because of the lack of an adequate model, the only reasonable channel capacity estimates in the auditory area have been made on the peripheral aspects of the channel. The channel capacity in bits per second for auditory signals has been calculated by the following formulation:

$$C = W\log_2 (1 + P/N)$$

where:

W = bandwidth of the channel in cycles per second

P/N = the additive power ration of the noise and signal

This can be calculated to be 50,000 bits per second with a bandwidth of 5,000 cps and a signal to noise ratio of 30 pounds (power ratio of 1,000). However, human information processing usually never exceeds 50 bits per second. The efficiency of the system is .1 per cent. Other theoretical computations have estimated the channel capacity of 10,000 bits per second with loud sounds. The average amount of information transfer of a single cochlear nerve fiber is about 0.3 bit per second (approximately 29,000 ganglion cells from the ear to the brain).

Other studies indicate that the ear is an information channel which has a larger capacity than is ever realized because the brain presumably acts as a scanner which receives information of interest at any particular time. It appears reasonable to assume that the 50 bits per second represent an upper limit for auditory information processing.

(2) Vision. It can be similarly estimated for the eye that the channel capacity for each eye is approximately 4.3×10^6 bits per second. The inclusion of color would probably raise this estimate. The empirical studies would also suggest an upper limit of information transfer at about 50 bits per second for vision. It, however, should be noted that other factors have influenced the obtained results. Such factors as redundancy of information, continuity of information, rate of presentation of information, method of presentation of information, etc., all influence the transmission rate.

One additional comment is necessary. It is evident that the theoretical limits of information processing by man with either the auditory or visual modality has never been approached. One possible explanation is that we have not as yet conceived means of properly presenting information to the operator or training operators to perform information processing. Utilization of this theoretical sensory information processing capability could represent a fantastic utility to any manned system. The replacement of many information processing devices with a man would reduce weight and cost provided proper presentation of information (displays) and training procedures could be developed.

In the consideration of information processing tasks which man must perform (judgments,intelligibility, perception, etc.), it can be observed that the theoretical limits of his performance with these tasks have also not been approached. The difficulty again appears to be the lack of proper techniques for inducing information processing and a lack of understanding some of the pertinent variables. This has been to some extent demonstrated in our own laboratories in terms of visual information processing by human subjects presented with target detection information. We have found that the human is capable of detection and processing information concerning targets at levels of resolution of about 20 foot ground resolution and at a 90 per cent correct identification level. However, the conditions of presentation and the type of information presented to the operator determine his ability to process this information.

2. Decision Making

Decision making is commonly divided according to whether it is carried out under conditions of certainty, risk or uncertainty. The following definitions are necessary for understanding these conditions.

(1) Certainty. If each is known to lead invaribly to a specific outcome.

(2) Risk. If each action leads to one of a set of possible specific outcomes, each outcome occurring with a known probability. The probabilities are assumed to be known for tne decision making.

(3) Uncertainty. If either action or both has as its consequence a set of possible specific outcomes, but where the possibilities of these outcomes are completely unknown or are not even meaningful.

Each of these conditions exists in the decision making role of man within the Apollo system. The direct quantification of human decision behaviors is, therefore, very difficult. It is dependent on the following factors:

(1) The type of conditions available during the decision time

(2) The type of information available to make a decision

(3) The cost or value of making a decision during a particular time period.

(4) The time period required for a decision.

One particular model which allows for some quantification of the operator's decision-response is signal detection theory. This model and the supporting research indicates that the threshold limit on the detection or decision as to the presence or absence of a signal is determined by varying the payoffs (gains) to the operator. As a function of this, the operator's probability of detection can be manipulated over a broad range by varying the payoffs. The broad ranges which the operator can manipulate his decisions increase his flexibility and allows him to perform decision functions based on the information presented to him and particular decision criteria at any point in time. Various ideal mathematical strategies have been developed when compared with human operator data indicates a non-statistical difference after a small number of adaptation trials.

It is of further interest to note that there is difficulty in programming similar mathematical strategies into automated computers. This may be due to the capacity channels required and mathematical limitations for programming automated computers. Further, the number of central nervous systems neurons available to the human operator is estimated to be approximately 10^{10} while the total estimated memory capacity is approximately 10^{13} to 10^{15} bits in retained information.

It again appears that the limit in decision making is not dependent on the human capability involved, but more precisely on the method of presentation of decision information and the method of decision making can be manipulated by the training of the operator to the extent that he can learn to act as an approximation of an ideal mathematical decision maker. In terms of speeds of successive decision, the automated computer appears to have the advantage but is limited in terms of the finite number of programs which can be placed in the computer memory.

3. Tracking and Control Behavior

The role of man within the Apollo system in tracking and control behavior should not be underestimated. Though many individuals believe that his tracking and control performance is limited by the environment (acceleration, weightlessness, etc.), required reaction times, the performance dynamics of the vehicle system, etc., there is reason to believe that other factors are more important.

Primary in the design of a manned tracking and control system is the transfer function which relates man to the machine. Until recently, man has been represented by linear or quasi-linear models. These models fail to take into consideration certain characteristics of the human operator which are not necessarily decrements. They are as follows:

(1) Human operators appear to respond discontinuously

(2) They appear to respond as if their internal time scales are somewhat quantized.

(3) They do not appear to give identical responses to identical stimuli.

It should appear obvious to the specialist in neurophysiology that evidence exists on the quantized time basis of the central nervous system. To the experimental psychologist, evidence exists which would cast doubts about measuring either identical responses or stimuli in replicated situations. In fact, the experimental psychologist utilizes varied experimental designs to insure at statistical certainty of replicated stimulus-response situations. Therefore, until evaluative non-linear techniques are developed and are readily utilized in the design of tracking and control systems, a true estimate of man's response capabilities in these areas is lacking.

Another area of scientific and technical ignorance should be discussed. The human operator in order to perform tracking and control tasks must be presented with applicable and useful information. This, of course, implies a display system which presents proper information. As yet, little advances in the proper representation of information to the operator for control tasks have been made. When limited by the environmental conditions such as in the Apollo system, the operator is left with only his display system as a means of communication with his vehicle and his environment.

Let us now consider some data on capabilities of the operator based on linear or quasi-linear models.

(1) A linear model of human operator behavior indicates the performance in tracking of low-frequency sinusoidal motion, however, this model does not appear applicable to rapid sinusoidal oscillations.

(2) Considering the use of a servo-mechanism model as a human operator is somewhat limited. This exists because the operator does not have an important feature of a servo mechanism. That is with Time (T) at infinity, a closed-loop system should adjust its output to equal a steady input without error. The human operator does not appear to function this way. Therefore, in order to correspond to a servo model, one has to introduce an attenuation factor (possibly proprioceptive feedback). This feedback would be negative in nature.

(3) There exists obvious differences among human transfer functions for different tracking tasks. However, time and trial variations are small for operators.

(4) In situations with simple tracking (no external dynamics) the operator's gain drops off rapidly and his phase lags behind with increasing frequency.

(5) In pursuit tracking tasks, the most important factor is to adjust the display scale factor until the target motion makes an appropriate movement on the display. In compensatory tracking, the amplitude of the error depends upon the accuracy of the operator, and the accuracy of the operator depends upon the amplitude of the error movement of the display. If the tracking target in a pursuit task moves slowly enough, the operator can follow it through wide excursions by moving along with it, and thereby achieve great relative accuracy. In a compensatory task, as long as he operates accurately, he does not have to move, since accurate operation keeps the error small.

It appears from the brief discussion above that the human operator's ability as a controller and tracker has never been fully exploited due to the lack of development of non-linear models. However, the available data on this type of performance with linear models indicates a great deal of capability. Further, valid data is available on operational performance of pilots with high-performance systems. Two determining factors should be emphasized in order to use this capability.

(a) The design of the control system which exploits human capability.

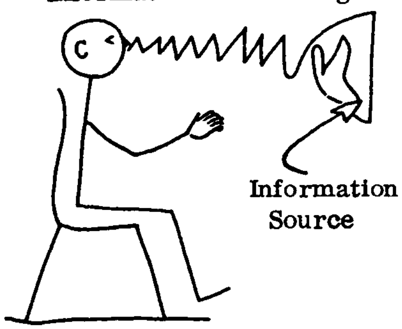
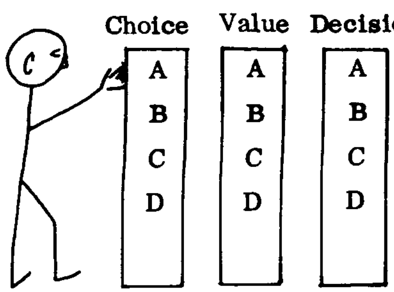
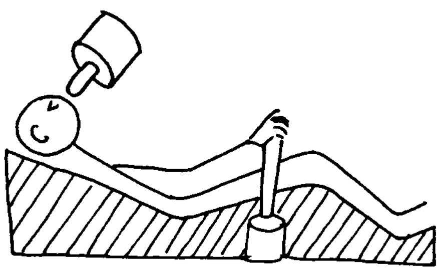
(b) The design of a display system which allows him to perform these control tasks with proper and usable information.

The results of these past discussions are summarized in Table 1-1 and Table 1-2. Table 1-2 requires some additional comments. This table is a comparison between the essential factors of an automated computer and a human decision maker. Any attempt at cross quantification between computer and man is difficult particularly when considering human advantages as flexibility and opportunism. However, the human appears capable of performing decision-functions except for speed of computations.

[redacted]

TABLE 1-1

MAN'S CAPABILITIES

Capabilities	Theoretical Capabilities	Achieved Capability	Important Factors
Information Processing 	10,000 to 50,000 bits per second Ability to learn	10 to 100 bits per second Ability to learn	Proper information displays Development of useful training techniques
Decision Cost of Making 	Memory elements available - 10^{10} neurons Memory capacity 10^{13} to 10^{15} bits Behaves as mathematically ideal, ability to learn	Behaves as decision-maker of a statistical variety Utilizes costs and value information to make de-decisions Behaves as likelihood estimator	Proper information displays Development of useful training techniques
Tracking and Control 	Nonlinear system Sensor-motor systems integrated Ability to learn Excellent sensor system Visual (4.3 x 10^{-6} bits per second	Responds discontinuously Feedback system Fair reaction time Human system completely integrated Use internal compensatory mechanisms	Use of nonlinear design models Proper information display

[redacted]

TABLE 1-2

Comparison of Computer with Human Decision-Maker

Signals	Coded	Coded, visual, pattern, acoustical, skin and smell
Rate	10^{12} to 10^{15} bits per second	100 bit per second achieved; 50,000 per second capability
Components available and easily packaged	10^{5} to 10^{6} in number 10^{-2} to 10° Cm^{3} in size	10^{10} nervous system cells (neurons) 10^{-8} to 10^{-6} Cm^{3}
Memory Capacity	10^{5} to 10^{8} bits	10^{13} to 10^{15} bits (estimated)
Advantages	Rapid calculations No emotional sensitivity Reliable (at low usage rate)	Ability to learn Does not need programming Reliable (at high usage rate) Opportunities Flexible

B. ANALYSIS OF MAN'S FUNCTIONS IN APOLLO

In attempting to analyze man's functions within the Apollo system, a number of methods were available. However, the validity of each of these methods is somewhat dependent on the criteria adopted as to the amount of influence man will have over the system and the related assumptions. The assumptions adopted were as follows:

(1) Man will be used in the system in a manner which will use his capabilities to a maximum.

(2) The system will not be primarily manual or automatic but will combine the best aspects of both modes of operation.

(3) Man will not be used in those conditions in which the environmental stress is high or in which his performance is limited by environmental stress. This assumption is based on the ability of automatized systems to perform the appropriate functions during these periods.

The methods used were a sequential activities analysis and time line function analysis. Each of these methods yields information as to the needed crew information requirements, crew responses, crew workload and work-rest cycle.

1. Apollo Sequential Activities Analysis

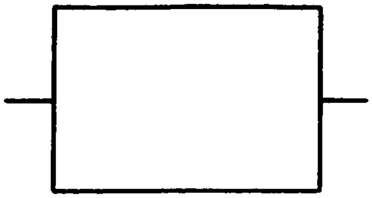
This method represents a way of analyzing certain human functions within a lunar orbit mission.

a. Description

The Apollo Sequential Activities Analysis is a step-by-step, or sequential, chart of events that occur within a typical lunar mission, from launch to touchdown, of the Apollo Vehicle. The diagram uses a technique similar to standard flow charting or block diagramming methods used by computer programmers. This type analysis was used because it was believed that certain types of information could not be determined by standard human factors analyses such as task analyses and second-by-second analyses. Essentially, the flow diagram shows qualitative and quantitative indications of those types of human activities or functions necessary to successfully complete a 14 day lunar orbit mission. It was determined, from study of the completed flow diagram, that the most important functions man accomplishes in the Apollo complex are information-processing, decision-making, discreet and continuous psychomotor activities and as a trouble-shooter and maintainer of on-board equipment. The first four of these are considered within the body of the analysis.

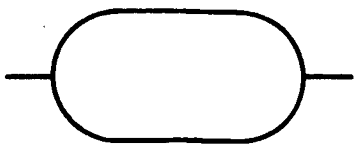
The flow diagram was also used as a basis for setting up the work-rest cycles. This was done by examining the approximate times involved for each series of tasks and re-estimated difficulty involved in accomplishing these tasks. It was also necessary to determine the number of crew members required to accomplish each mission function (e.g., navigational fix, midcourse guidance correction, systems check, etc.). A time base was laid out and many work-rest cycles examined until an acceptable one was found to fit the mission. This will be discussed in detail in another section. The analysis is presented with the interpolative symbology.

b. Terminology-symbology and analysis



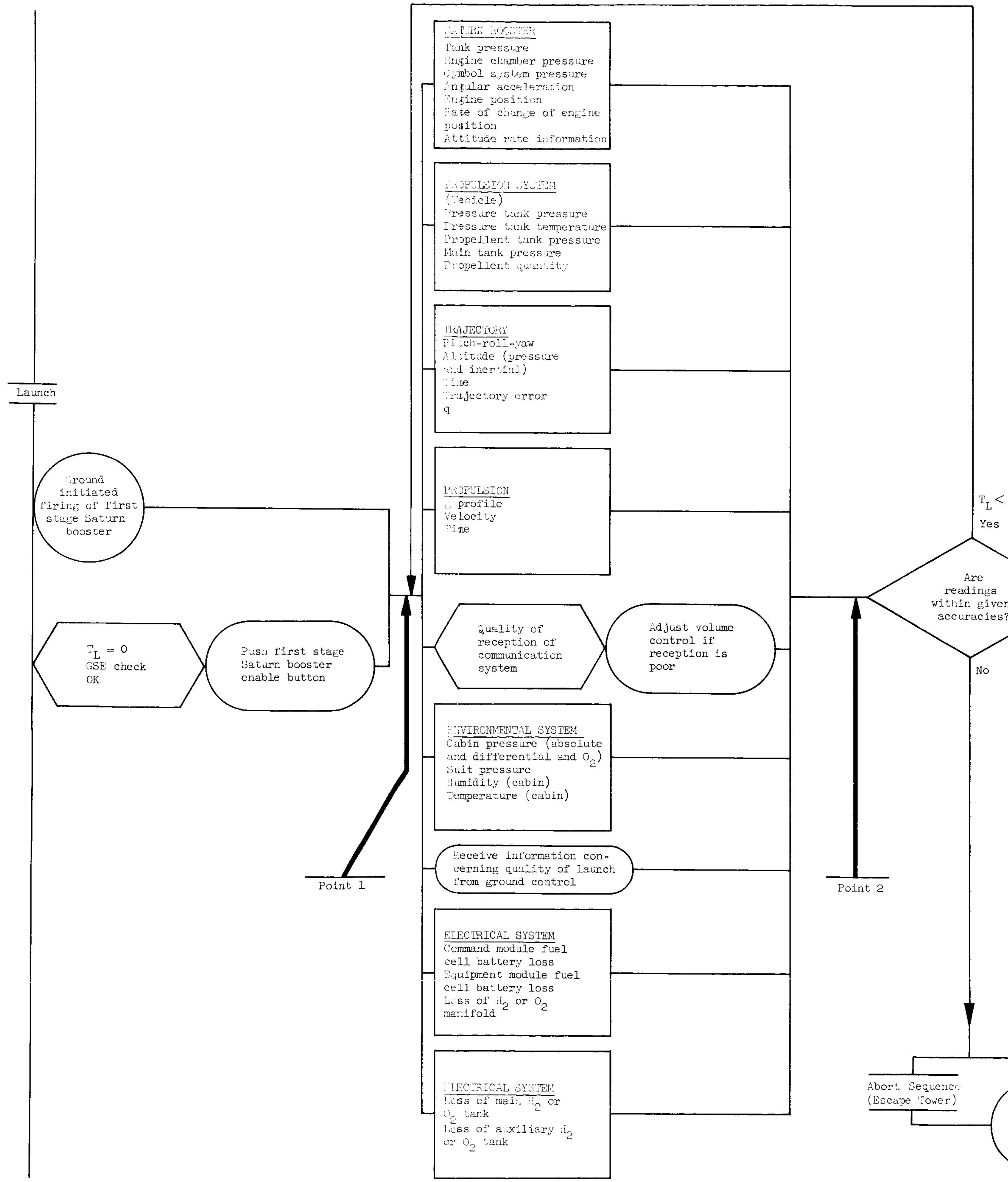
Human monitoring behavior

Communication activity involving one or more crew members (may either be from ground to vehicle or vice-versa)

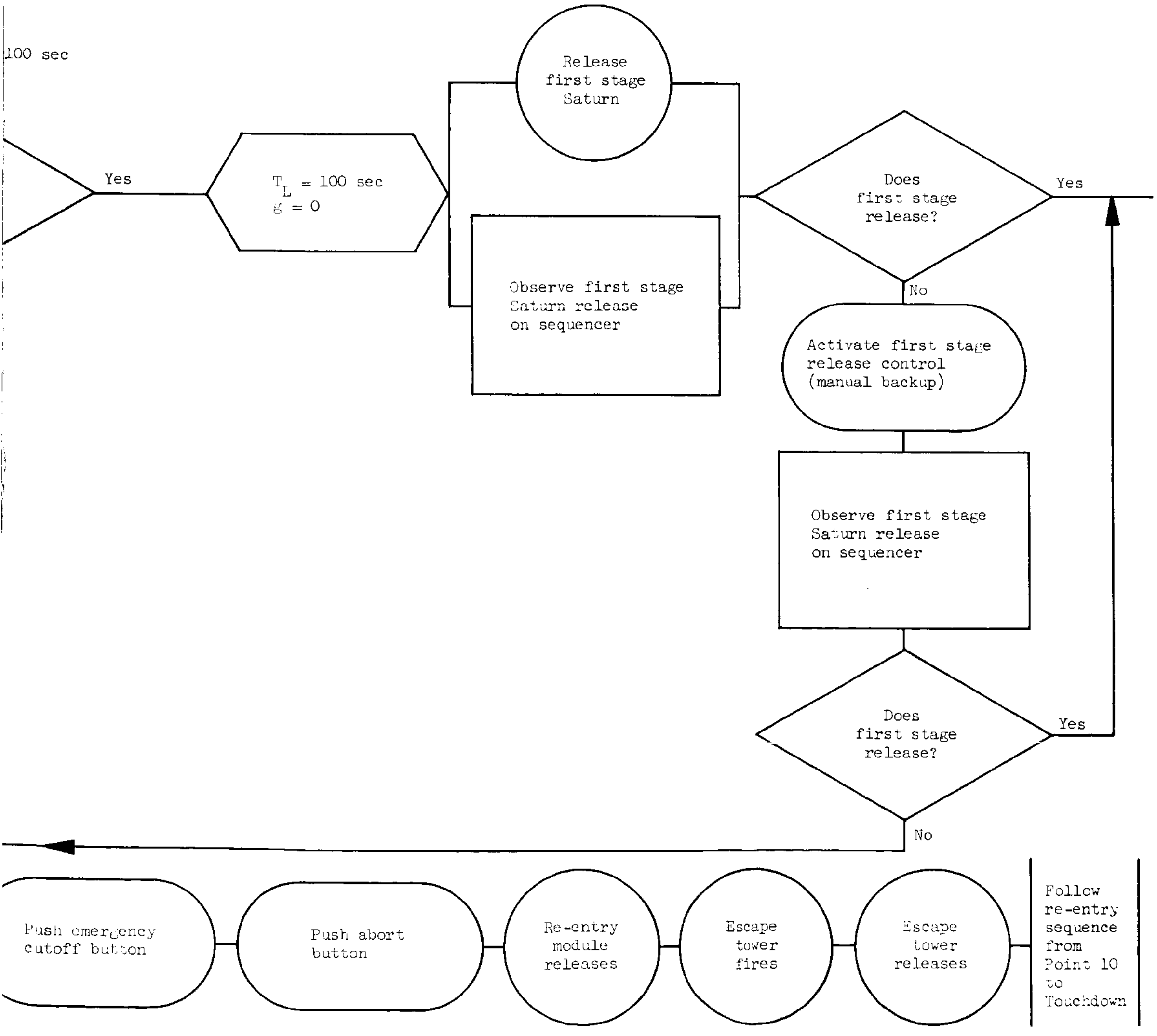


Human motor activity

[redacted]

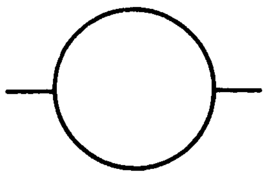


[redacted]

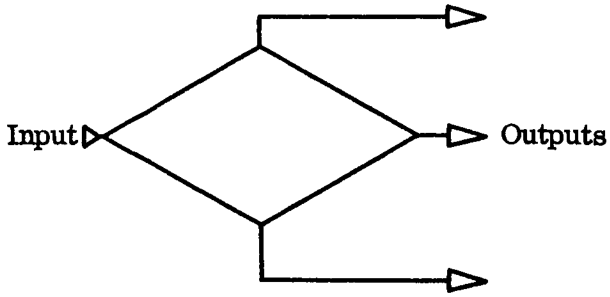


100 sec
Release first stage Saturn
Yes
T_L = 100 sec
g = 0
Observe first stage Saturn release on sequencer
Does first stage release?
Yes
No
Activate first stage release control (manual backup)
Observe first stage Saturn release on sequencer
Does first stage release?
Yes
No
Push emergency cutoff button
Push abort button
Re-entry module releases
Escape tower fires
Escape tower releases
Follow re-entry sequence from Point 10 to Touchdown

Information which tells a human when to initiate a particular task (always used immediately preceding the above three symbols)

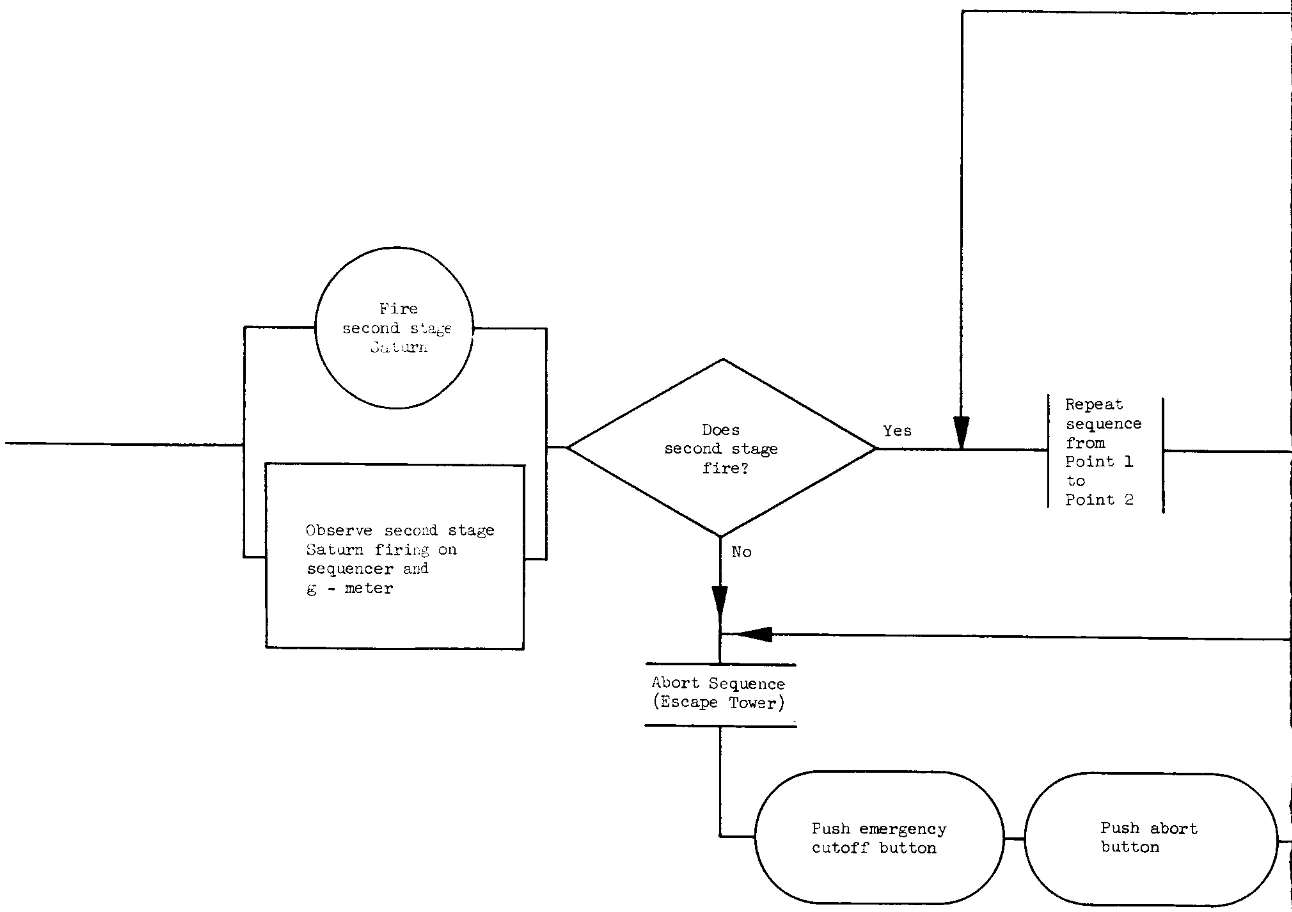


Machine function (involves no human activity)

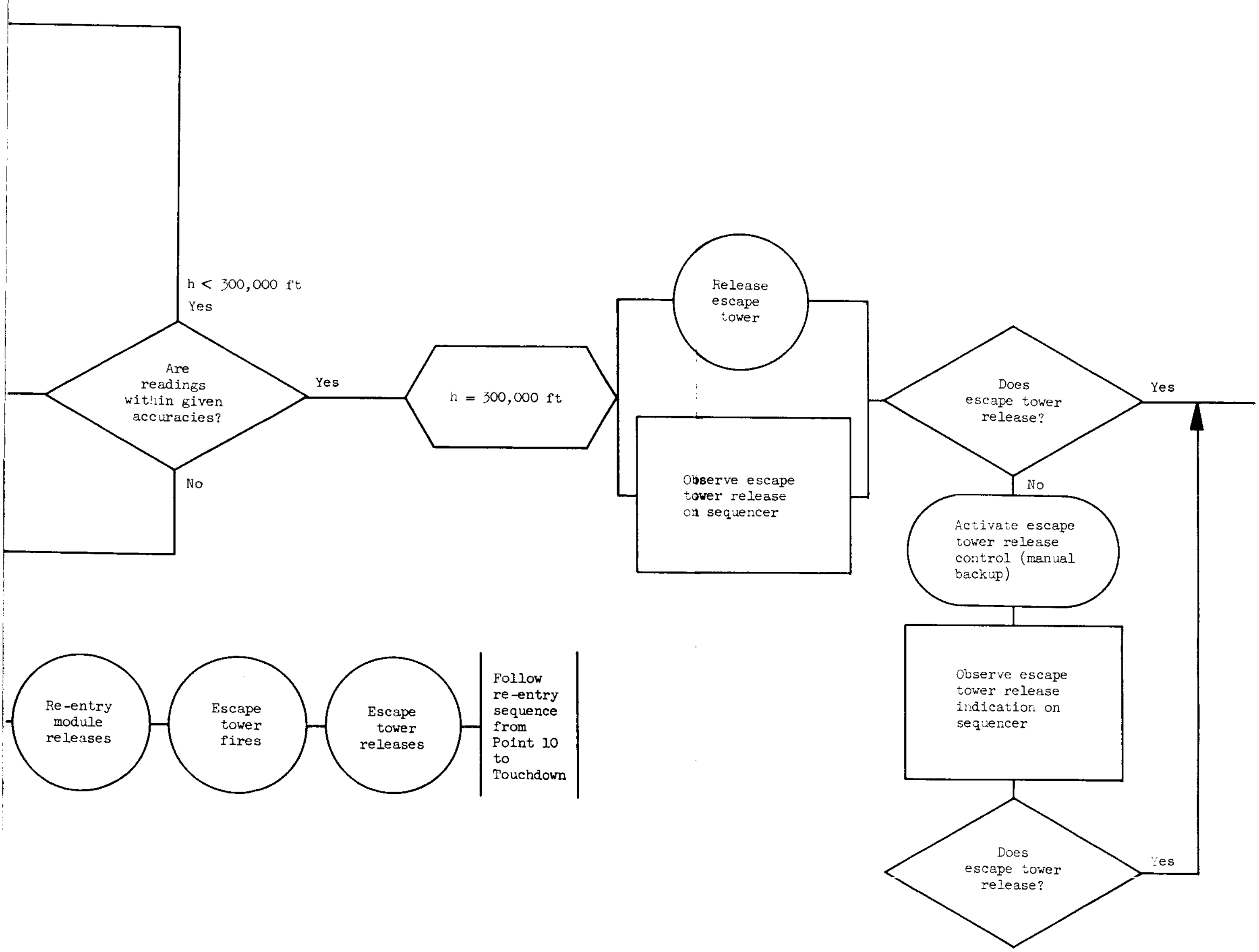


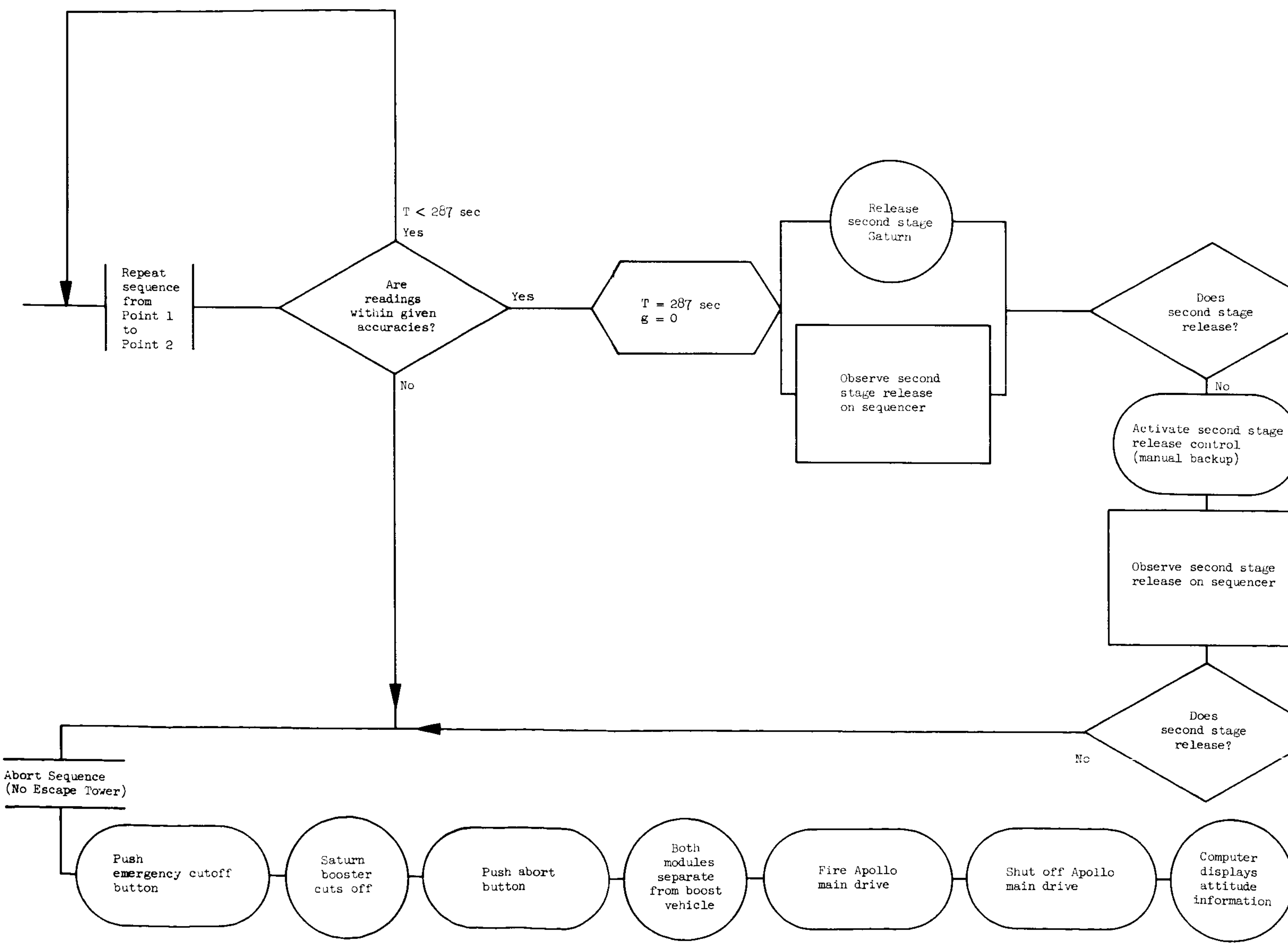
Decision box (always human decision)-this symbol indicates that in the event that two or more different conditions exists, then there will be two or more possible sequences of events occurring)

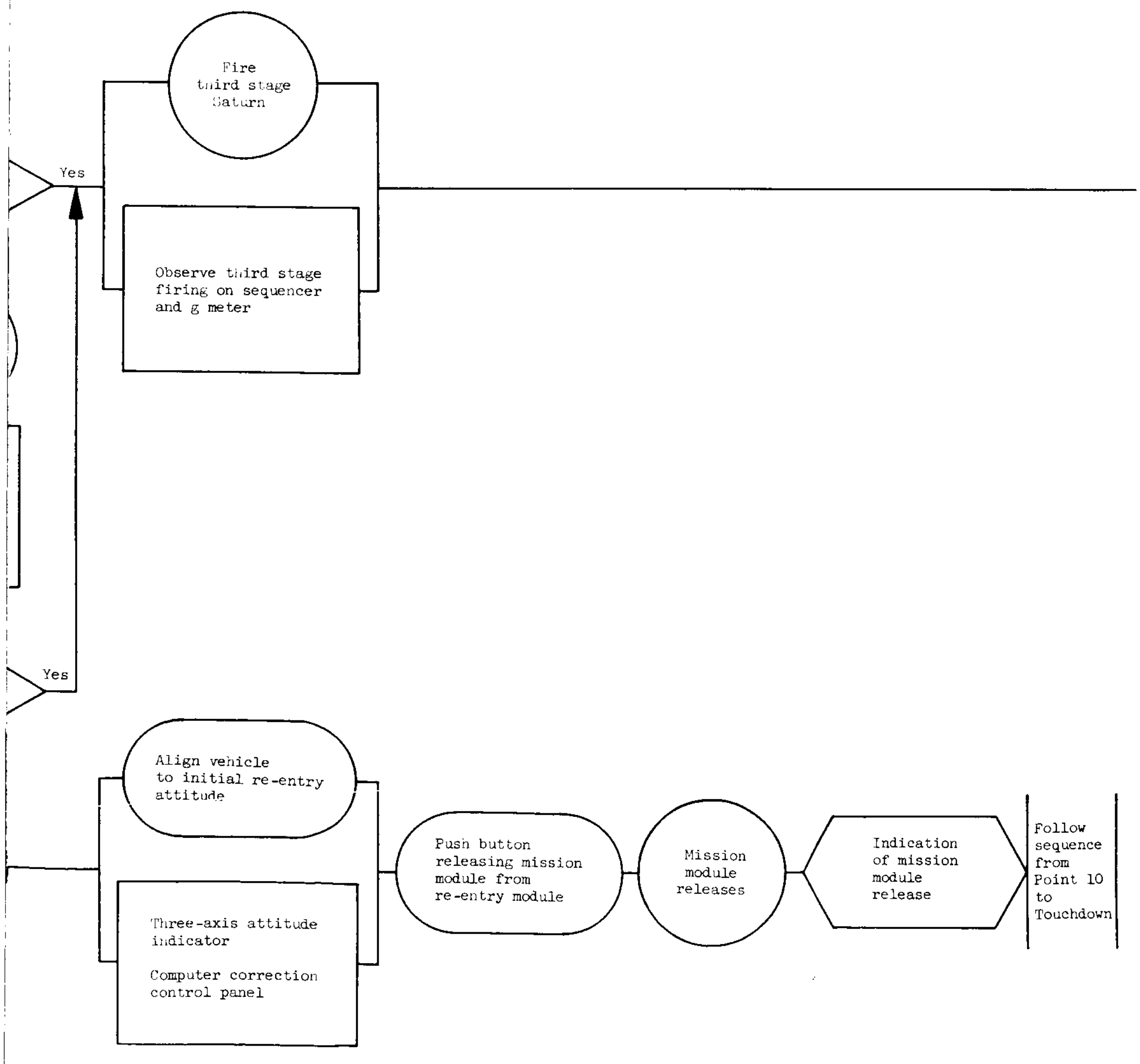
c. Apollo sequential activities flow diagram for lunar orbit mission


Fire second stage Saturn
Observe second stage Saturn firing on sequencer and g - meter
Does second stage fire?
Yes
Repeat sequence from Point 1 to Point 2
No
Abort Sequence (Escape Tower)
Push emergency cutoff button
Push abort button

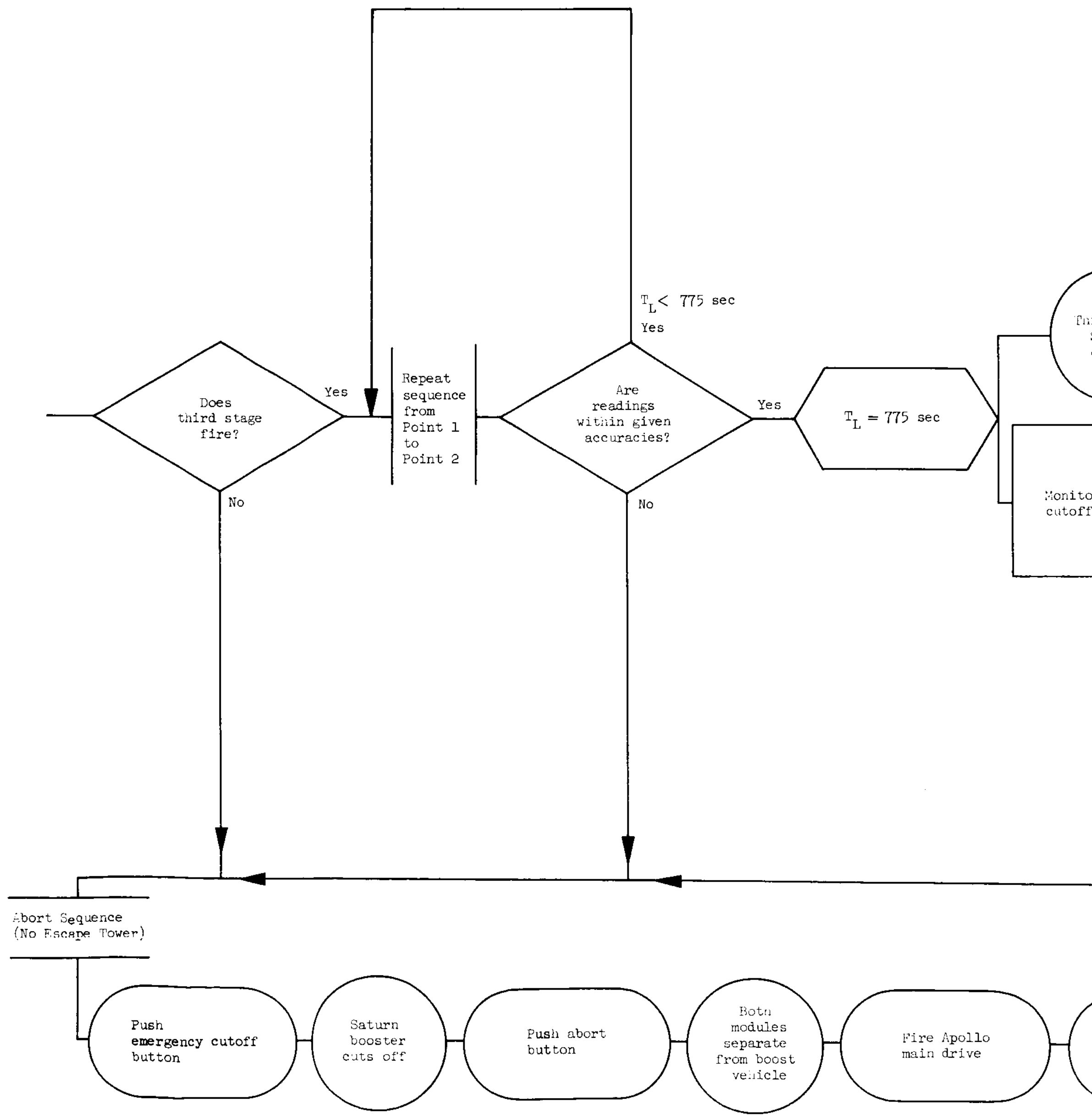
E


h < 300,000 ft
Yes
Are readings within given accuracies?
Yes
No
h = 300,000 ft
Release escape tower
Observe escape tower release on sequencer
Does escape tower release?
Yes
No
Activate escape tower release control (manual backup)
Observe escape tower release indication on sequencer
Does escape tower release?
Yes
Re-entry module releases
Escape tower fires
Escape tower releases
Follow re-entry sequence from Point 10 to Touchdown


T < 287 sec
Yes
Repeat sequence from Point 1 to Point 2
Are readings within given accuracies?
Yes
No
T = 287 sec
g = 0
Release second stage Saturn
Observe second stage release on sequencer
Does second stage release?
No
Activate second stage release control (manual backup)
Observe second stage release on sequencer
Does second stage release?
No
Abort Sequence (No Escape Tower)
Push emergency cutoff button
Saturn booster cuts off
Push abort button
Both modules separate from boost vehicle
Fire Apollo main drive
Shut off Apollo main drive
Computer displays attitude information

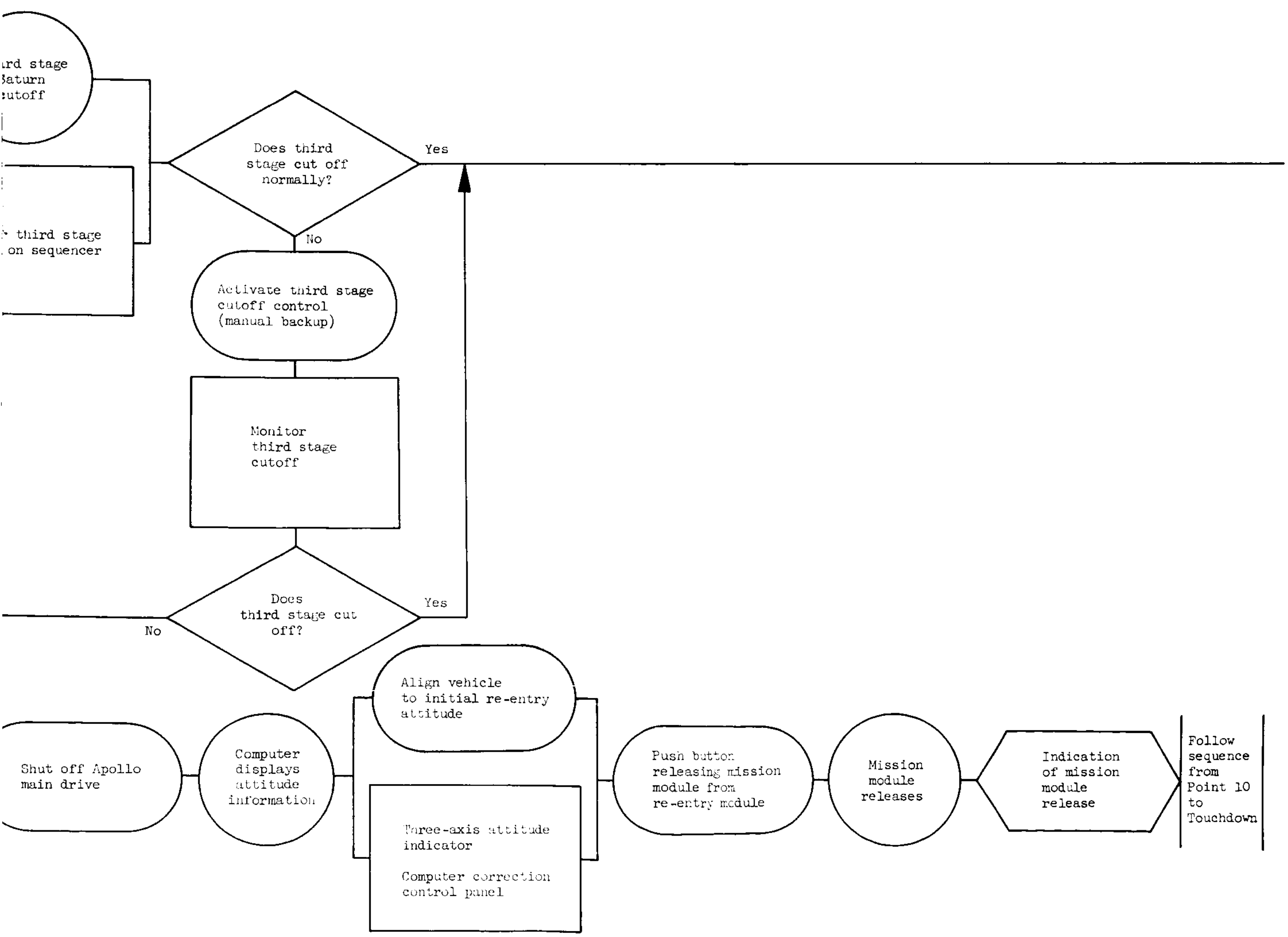


Yes
Fire third stage Saturn
Observe third stage firing on sequencer and g meter
Yes
Align vehicle to initial re-entry attitude
Three-axis attitude indicator
Computer correction control panel
Push button releasing mission module from re-entry module
Mission module releases
Indication of mission module release
Follow sequence from Point 10 to Touchdown

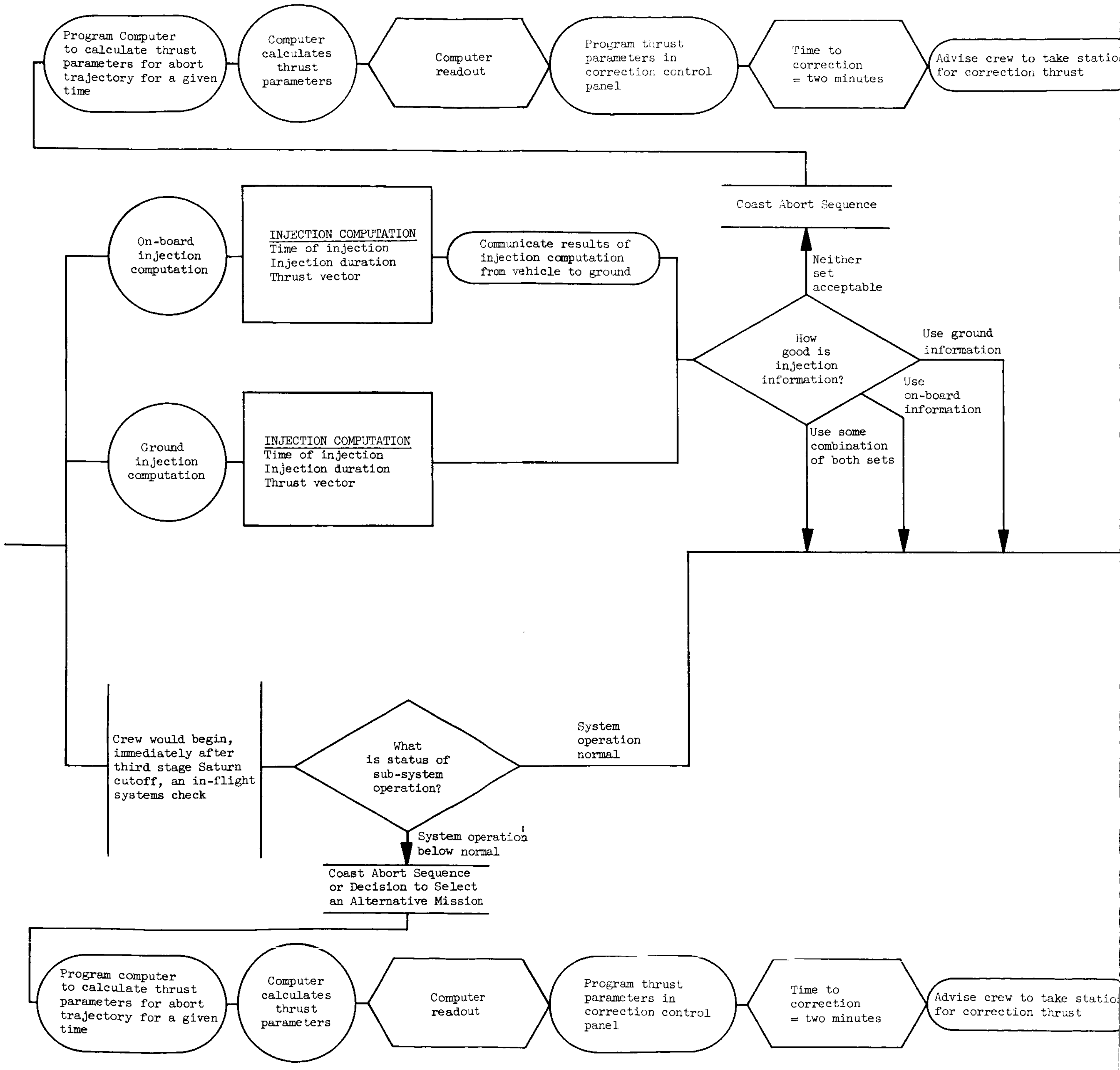


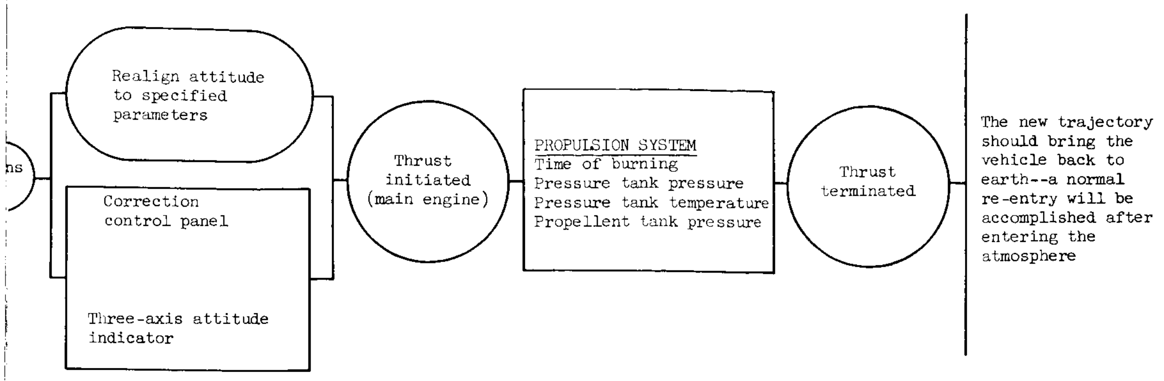
$T_L <$ 775 sec
Yes
Does third stage fire?
Yes
No
Repeat sequence from Point 1 to Point 2
Are readings within given accuracies?
Yes
No
T_L = 775 sec
Monito cutoff
Abort Sequence (No Escape Tower)
Push emergency cutoff button
Saturn booster cuts off
Push abort button
Both modules separate from boost vehicle
Fire Apollo main drive

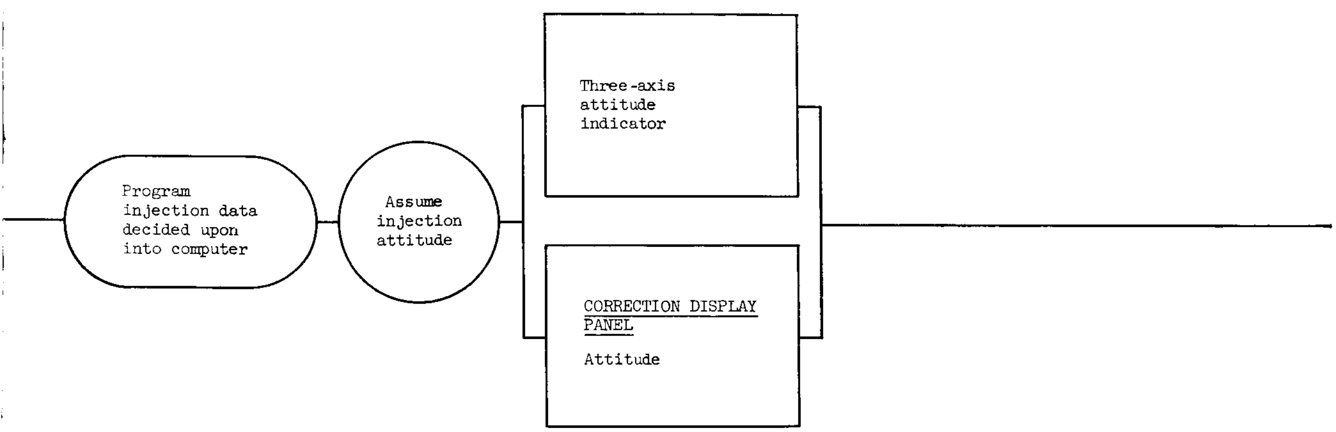
[redacted]

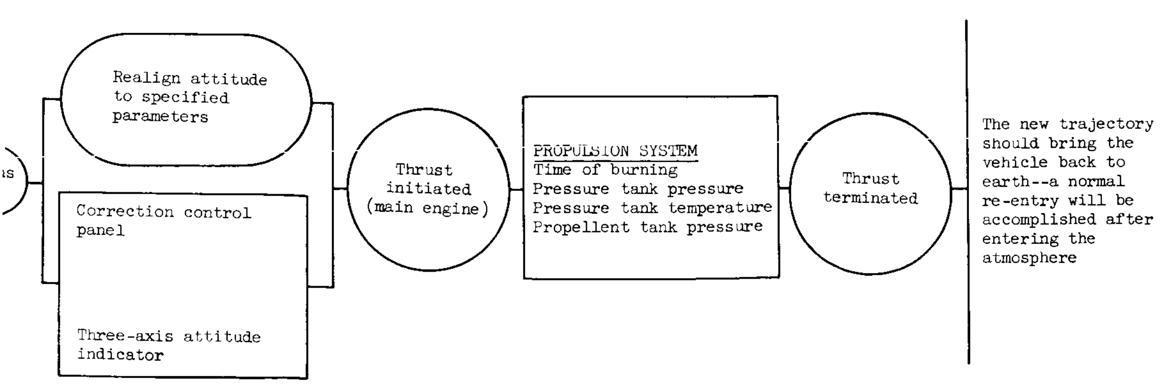


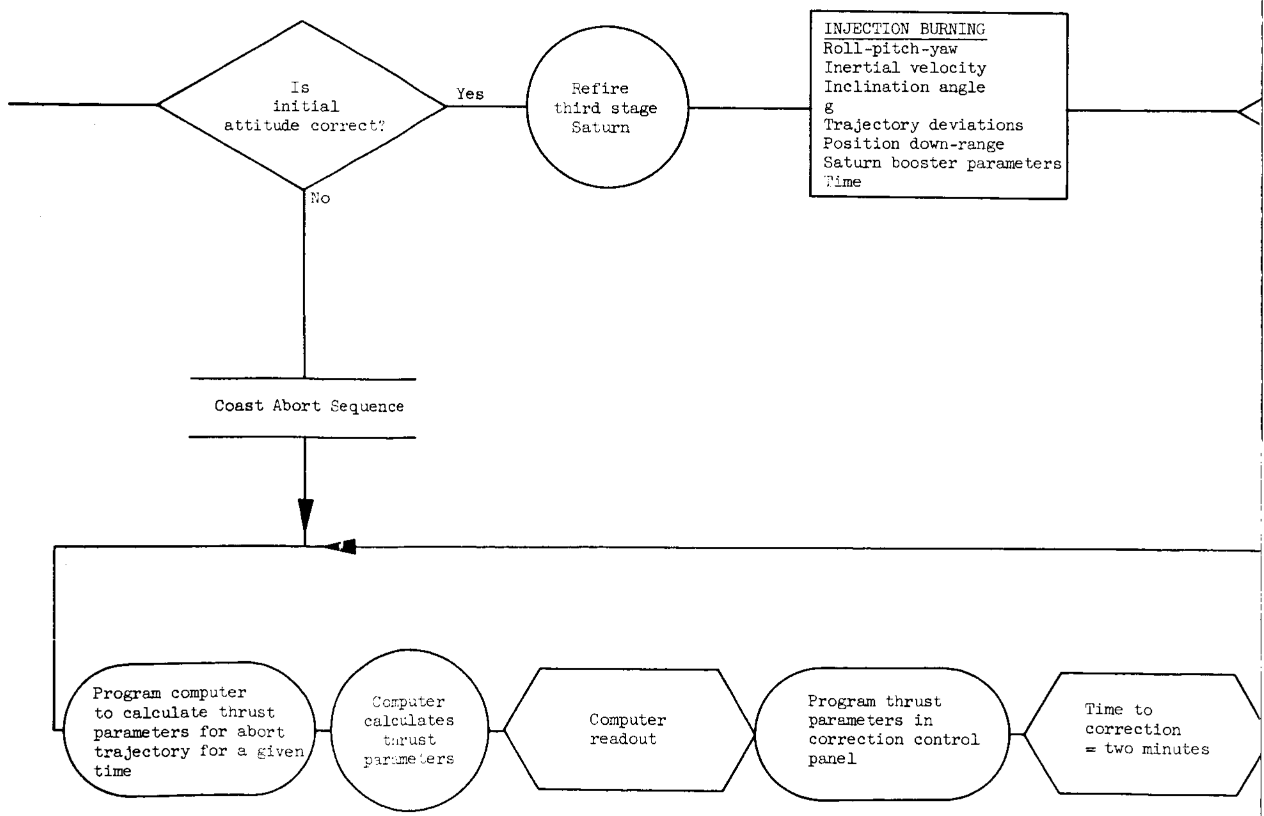
[redacted]


Program Computer to calculate thrust parameters for abort trajectory for a given time
Computer calculates thrust parameters
Computer readout
Program thrust parameters in correction control panel
Time to correction = two minutes
Advise crew to take statio
for correction thrust
Coast Abort Sequence
Neither set acceptable
On-board injection computation
INJECTION COMPUTATION
Time of injection
Injection duration
Thrust vector
Communicate results of injection computation from vehicle to ground
How good is injection information?
Use ground information
Use on-board information
Use some combination of both sets
Ground injection computation
INJECTION COMPUTATION
Time of injection
Injection duration
Thrust vector
Crew would begin, immediately after third stage Saturn cutoff, an in-flight systems check
What is status of sub-system operation?
System operation normal
System operation below normal
Coast Abort Sequence or Decision to Select an Alternative Mission
Program computer to calculate thrust parameters for abort trajectory for a given time
Computer calculates thrust parameters
Computer readout
Program thrust parameters in correction control panel
Time to correction = two minutes
Advise crew to take statio
for correction thrust


ns
Realign attitude to specified parameters
Correction control panel
Three-axis attitude indicator
Thrust initiated (main engine)
PROPULSION SYSTEM
Time of burning
Pressure tank pressure
Pressure tank temperature
Propellent tank pressure
Thrust terminated
The new trajectory should bring the vehicle back to earth--a normal re-entry will be accomplished after entering the atmosphere

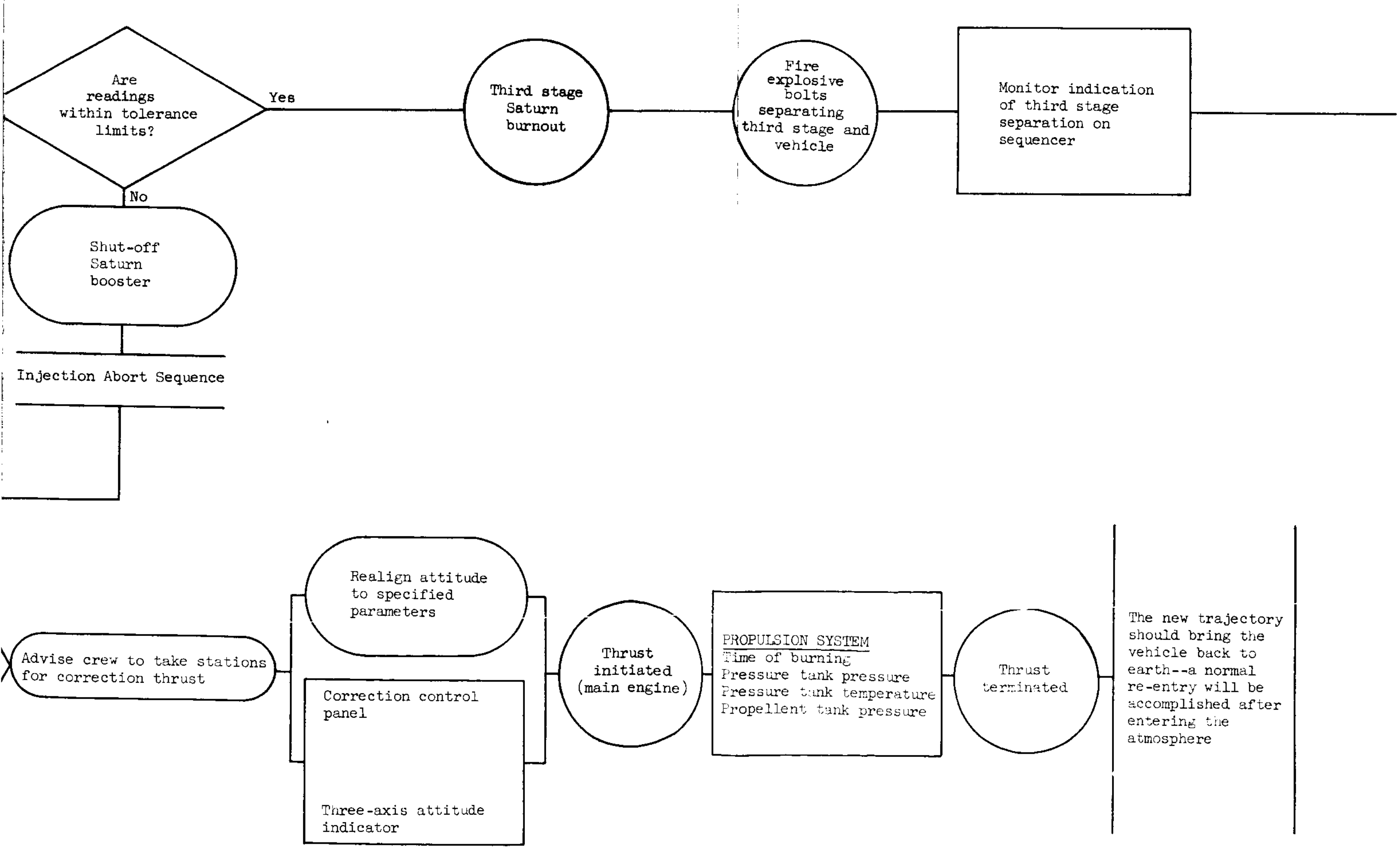

Program injection data decided upon into computer
Assume injection attitude
Three-axis attitude indicator
CORRECTION DISPLAY PANEL
Attitude


is
Realign attitude to specified parameters
Correction control panel
Three-axis attitude indicator
Thrust initiated (main engine)
PROPULSION SYSTEM
Time of burning
Pressure tank pressure
Pressure tank temperature
Propellent tank pressure
Thrust terminated
The new trajectory should bring the vehicle back to earth--a normal re-entry will be accomplished after entering the atmosphere

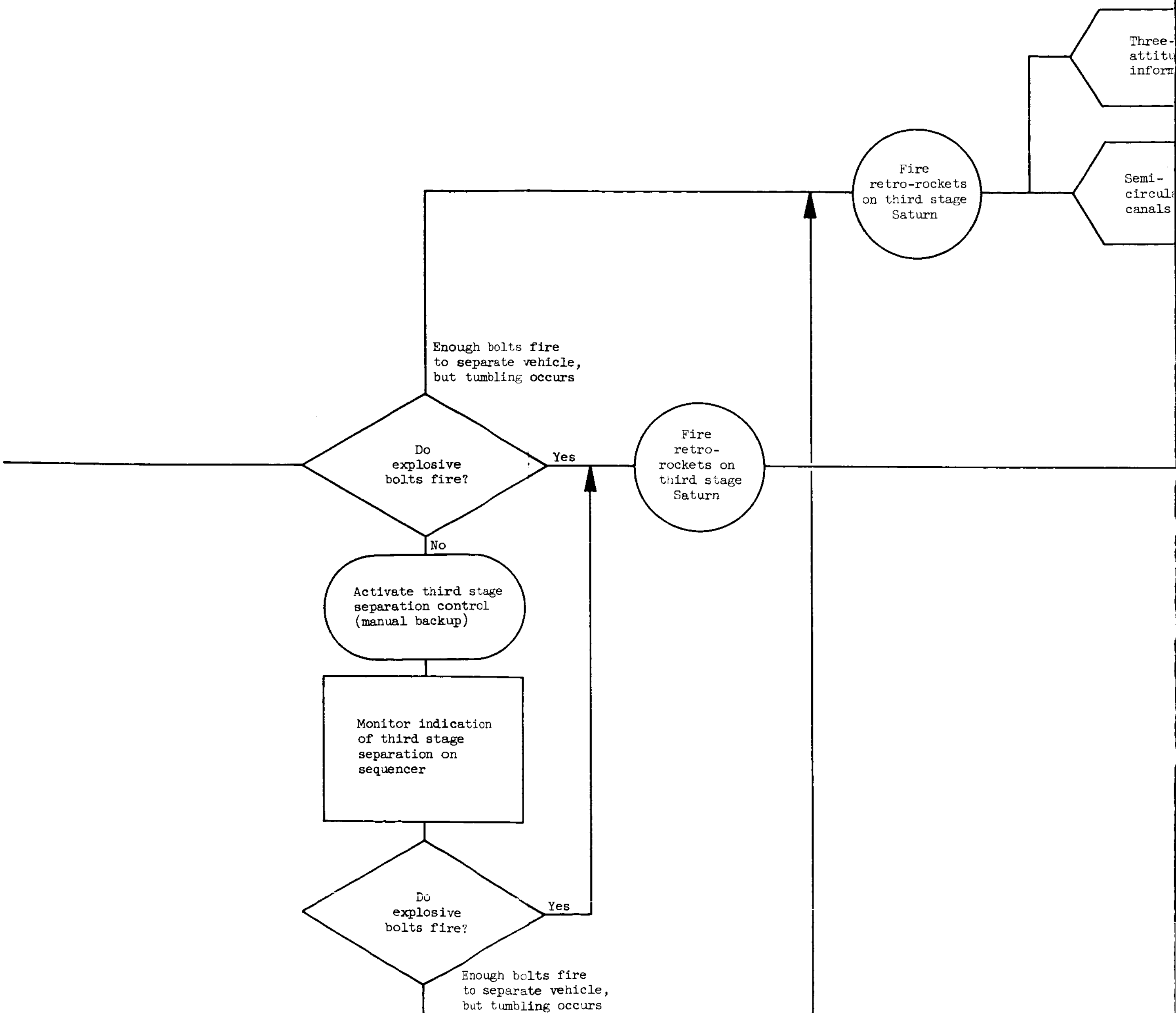


Is initial attitude correct?
Yes
No
Refire third stage Saturn
INJECTION BURNING
Roll-pitch-yaw
Inertial velocity
Inclination angle
g
Trajectory deviations
Position down-range
Saturn booster parameters
Time
Coast Abort Sequence
Program computer to calculate thrust parameters for abort trajectory for a given time
Computer calculates thrust parameters
Computer readout
Program thrust parameters in correction control panel
Time to correction = two minutes

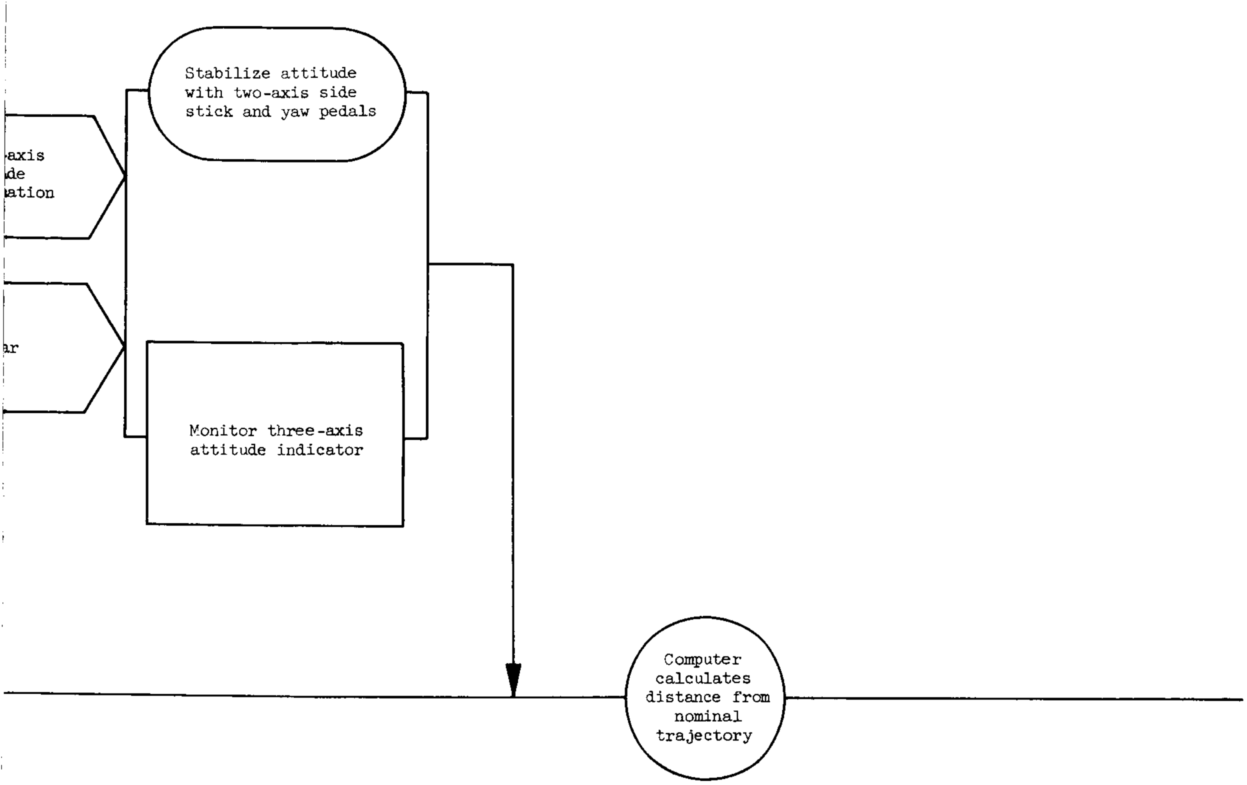
E

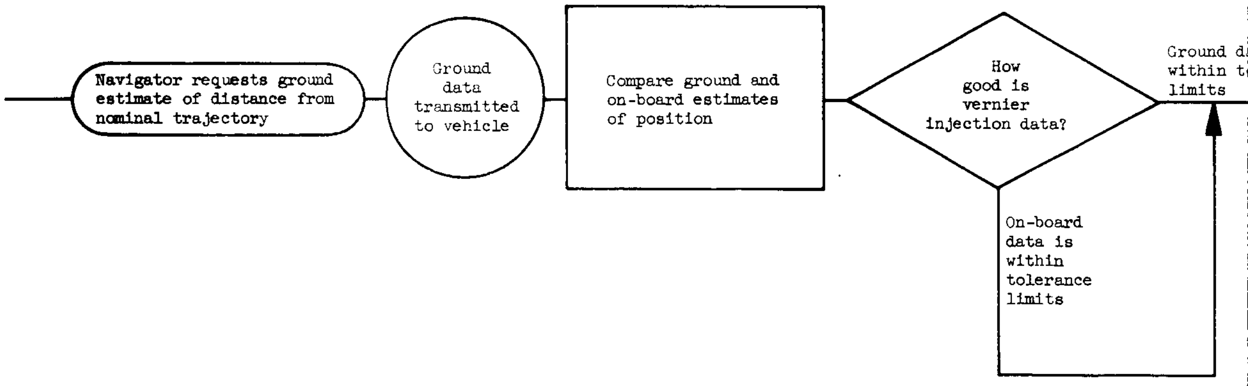

Are readings within tolerance limits?
Yes
No
Third stage Saturn burnout
Fire explosive bolts separating third stage and vehicle
Monitor indication of third stage separation on sequencer
Shut-off Saturn booster
Injection Abort Sequence
Advise crew to take stations for correction thrust
Realign attitude to specified parameters
Correction control panel
Three-axis attitude indicator
Thrust initiated (main engine)
PROPULSION SYSTEM
Time of burning
Pressure tank pressure
Pressure tank temperature
Propellent tank pressure
Thrust terminated
The new trajectory should bring the vehicle back to earth--a normal re-entry will be accomplished after entering the atmosphere

[redacted]

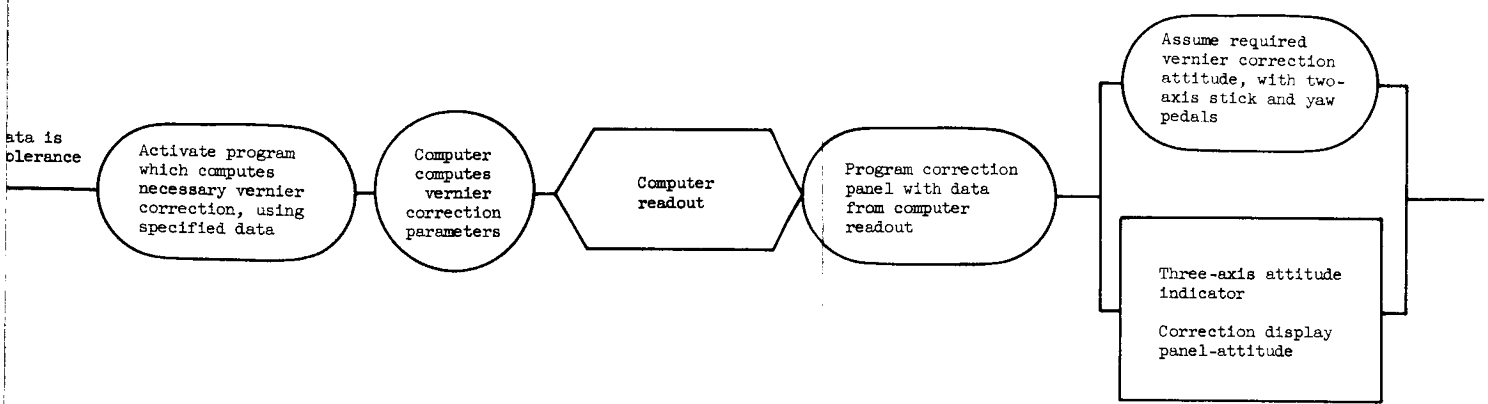


[redacted]

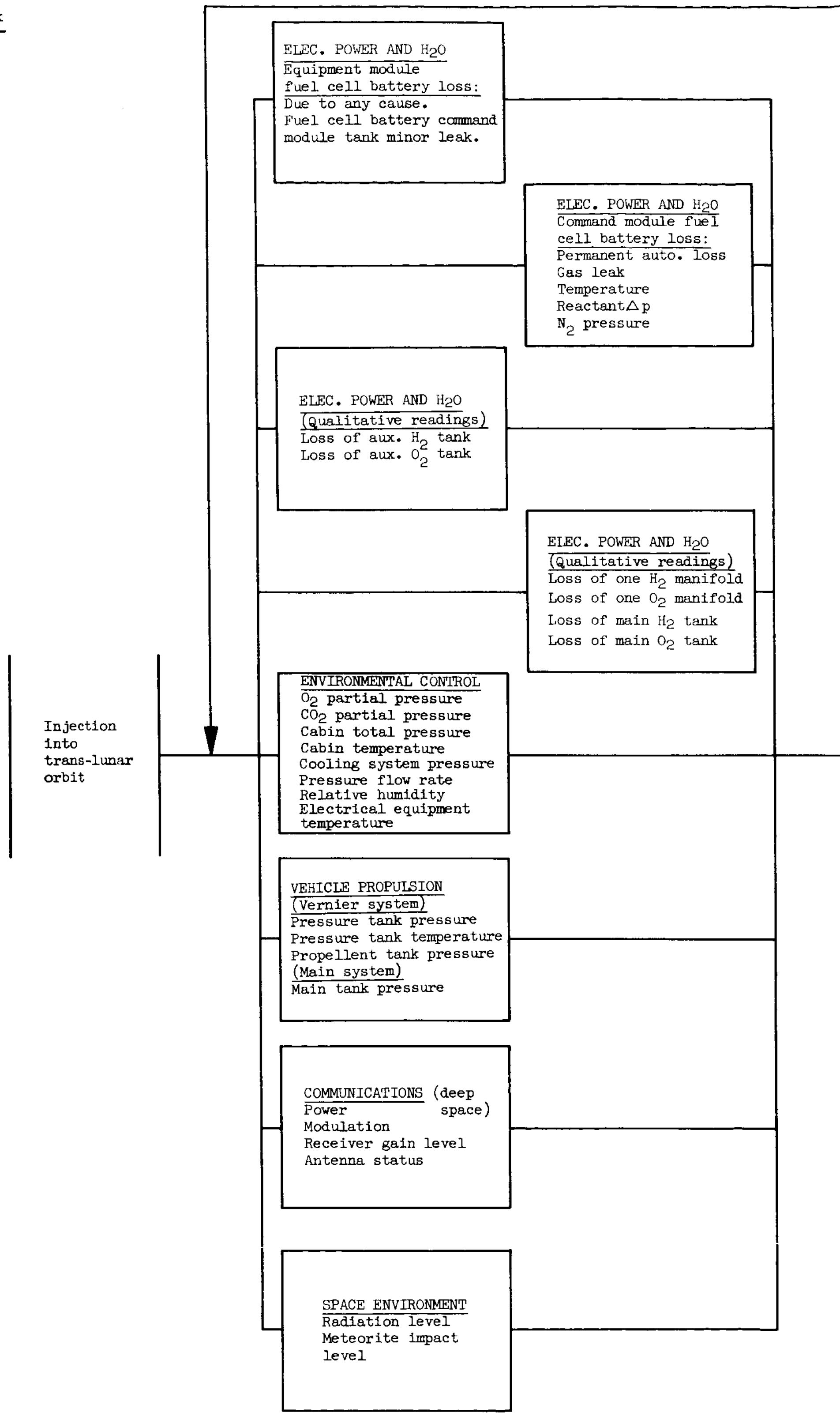

Stabilize attitude with two-axis side stick and yaw pedals
-axis
de
ation
ar
Monitor three-axis attitude indicator
Computer calculates distance from nominal trajectory

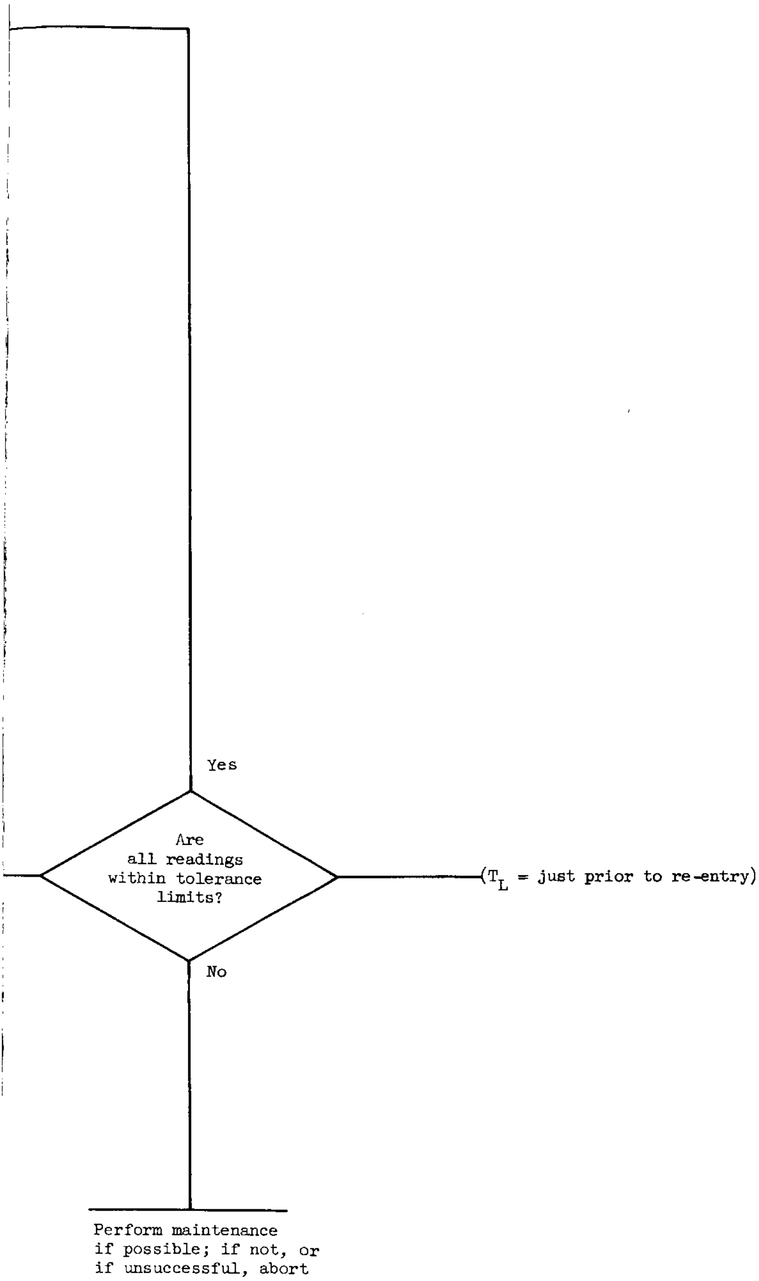


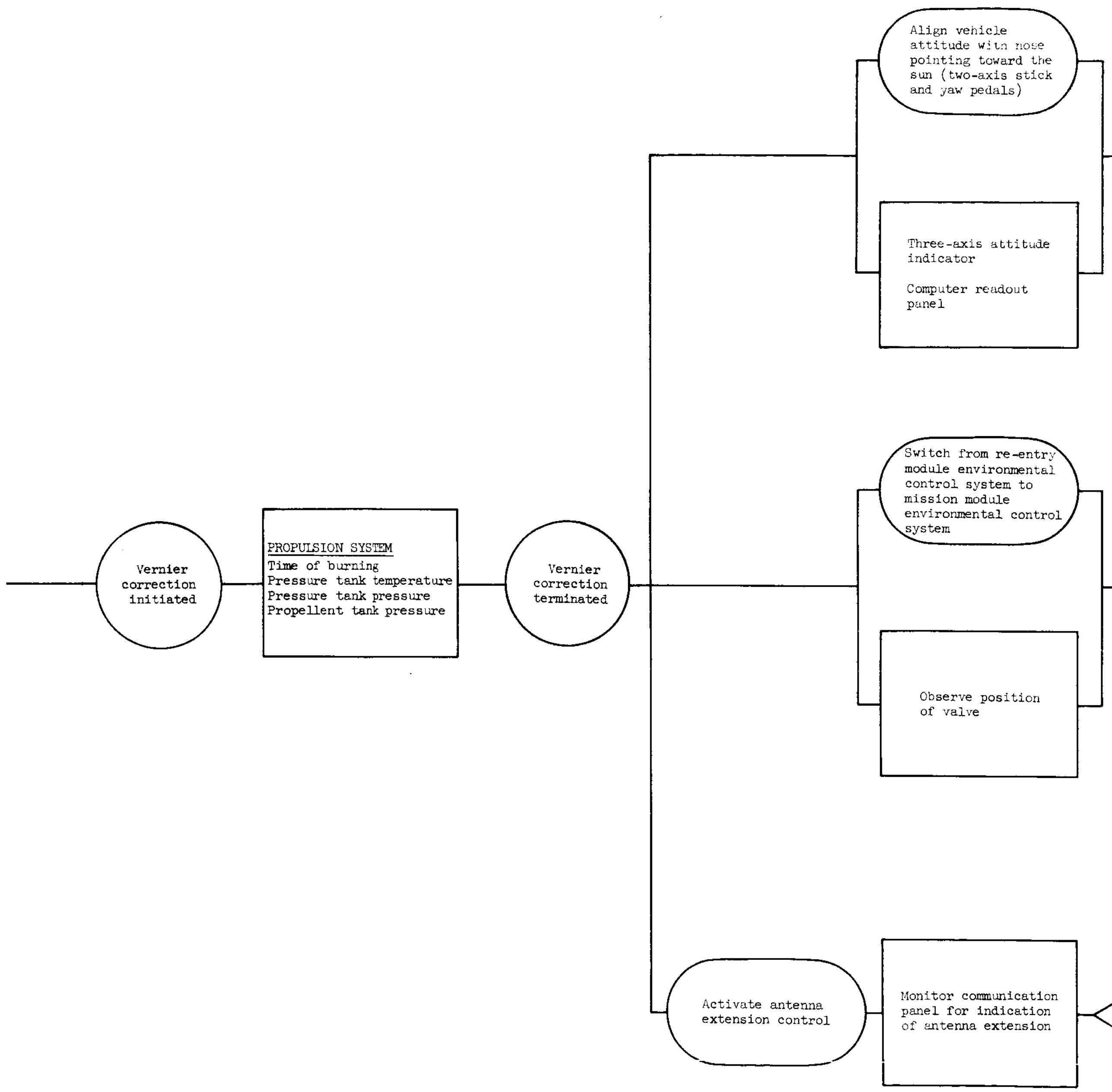
Navigator requests ground estimate of distance from nominal trajectory
Ground data transmitted to vehicle
Compare ground and on-board estimates of position
How good is vernier injection data?
Ground d
within t
limits
On-board data is within tolerance limits


ata is
olerance
Activate program which computes necessary vernier correction, using specified data
Computer computes vernier correction parameters
Computer readout
Program correction panel with data from computer readout
Assume required vernier correction attitude, with two-axis stick and yaw pedals
Three-axis attitude indicator
Correction display panel-attitude

Continuous Systems Monitoring Task

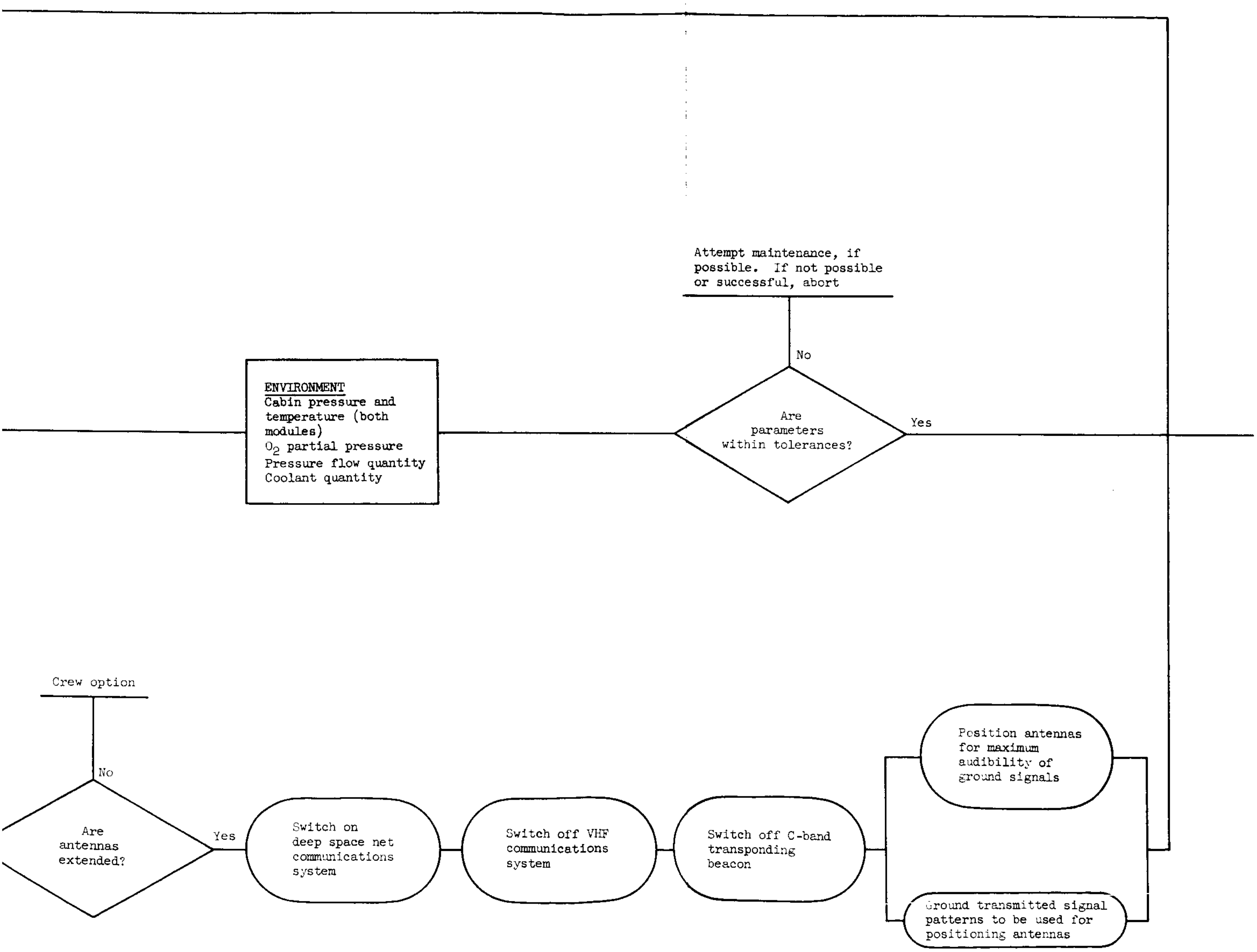



Yes
Are all readings within tolerance limits?
$(T_L$ = just prior to re-entry)
No
Perform maintenance if possible; if not, or if unsuccessful, abort

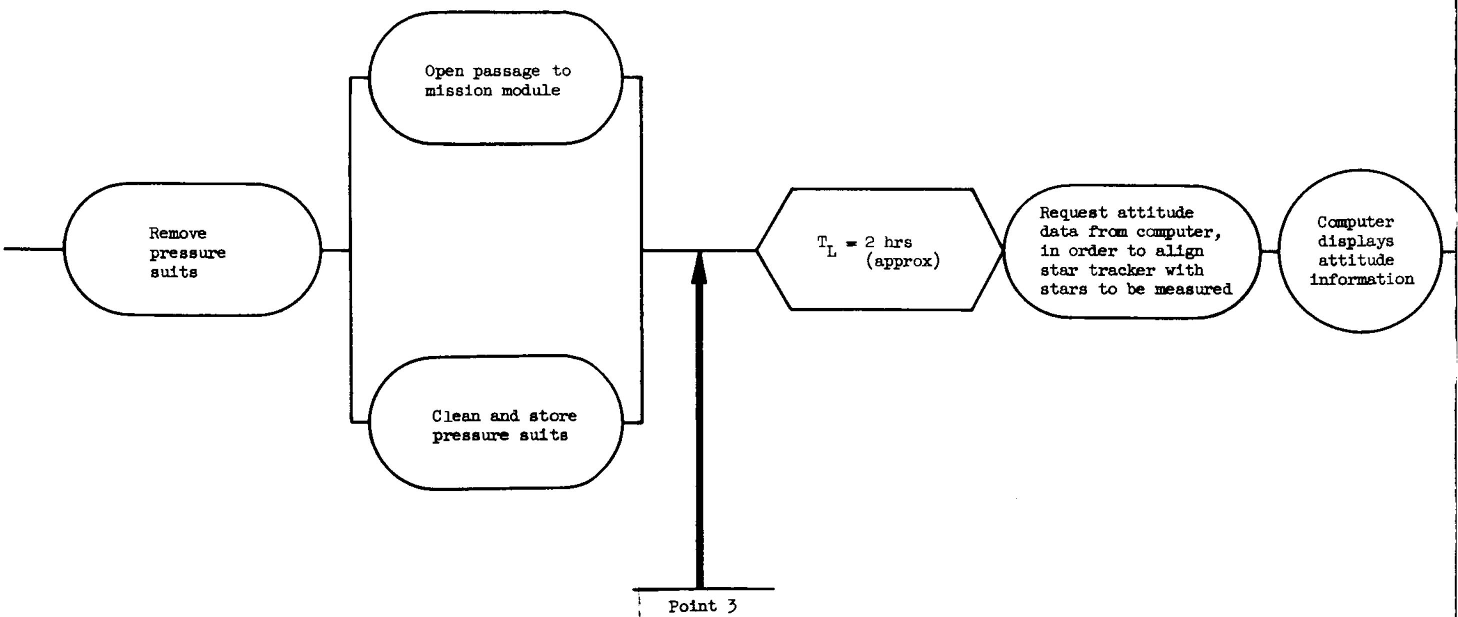


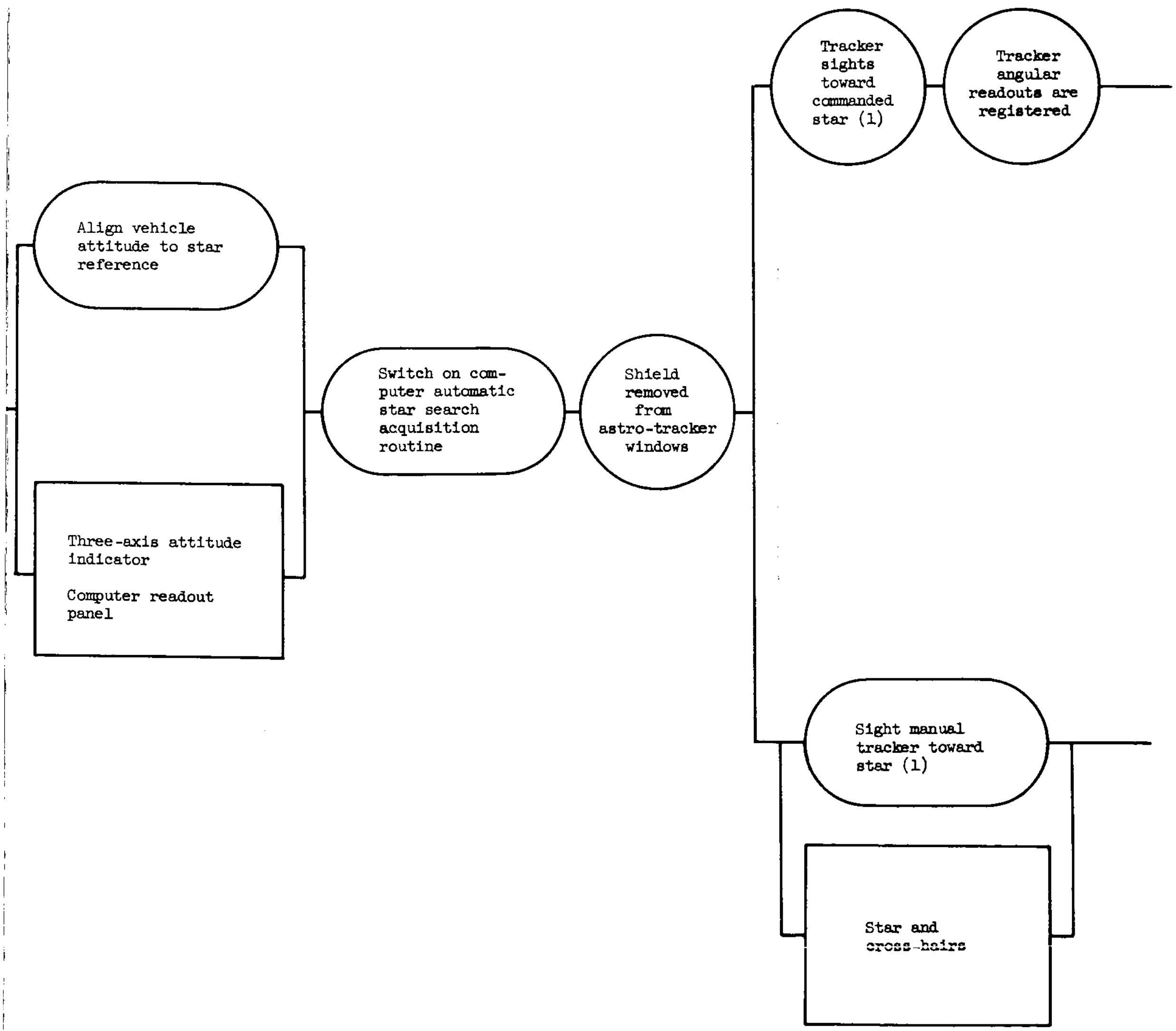
Align vehicle attitude with nose pointing toward the sun (two-axis stick and yaw pedals)
Three-axis attitude indicator
Computer readout panel
Switch from re-entry module environmental control system to mission module environmental control system
Vernier correction initiated
PROPULSION SYSTEM
Time of burning
Pressure tank temperature
Pressure tank pressure
Propellant tank pressure
Vernier correction terminated
Observe position of valve
Activate antenna extension control
Monitor communication panel for indication of antenna extension

[redacted]

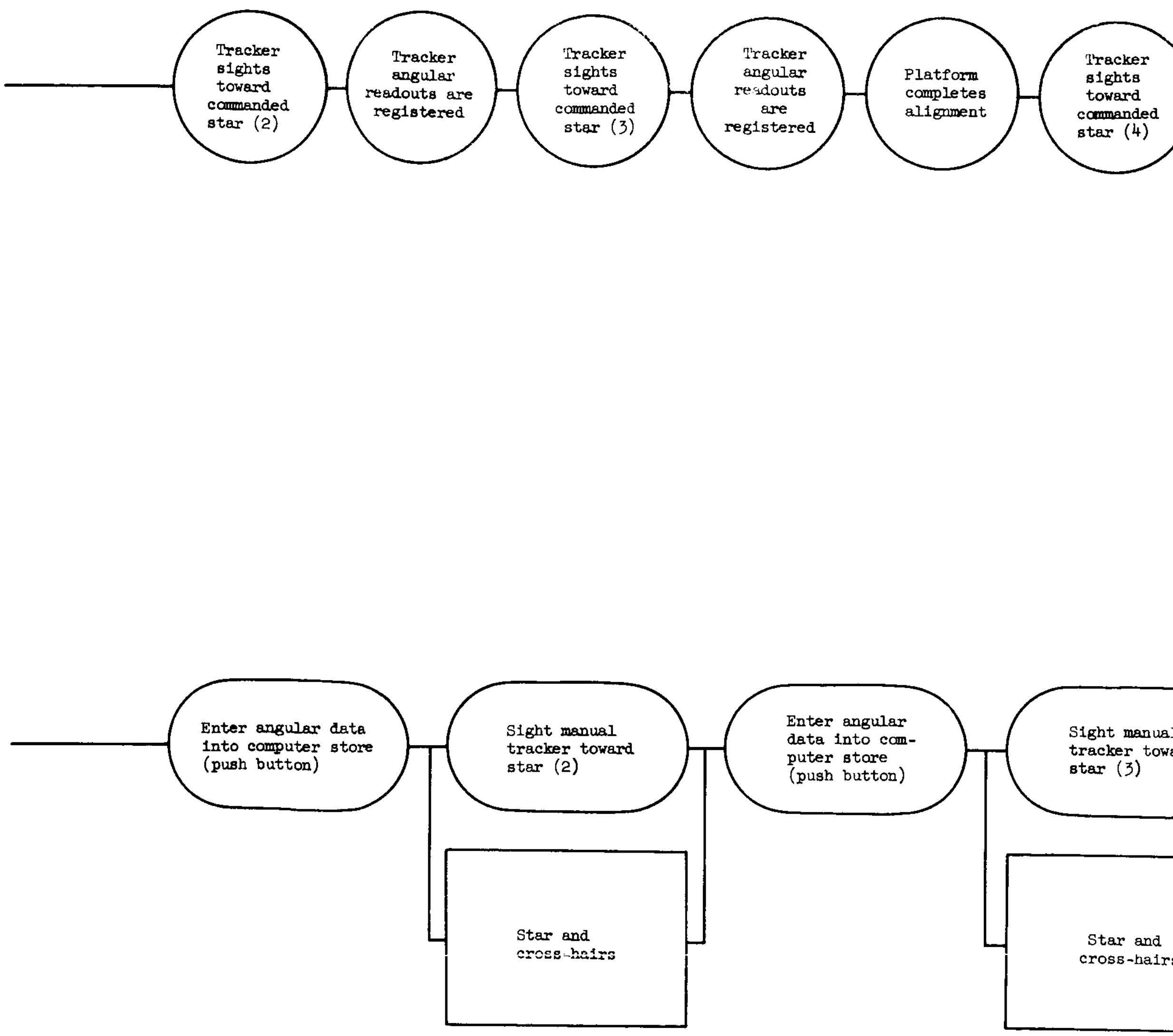


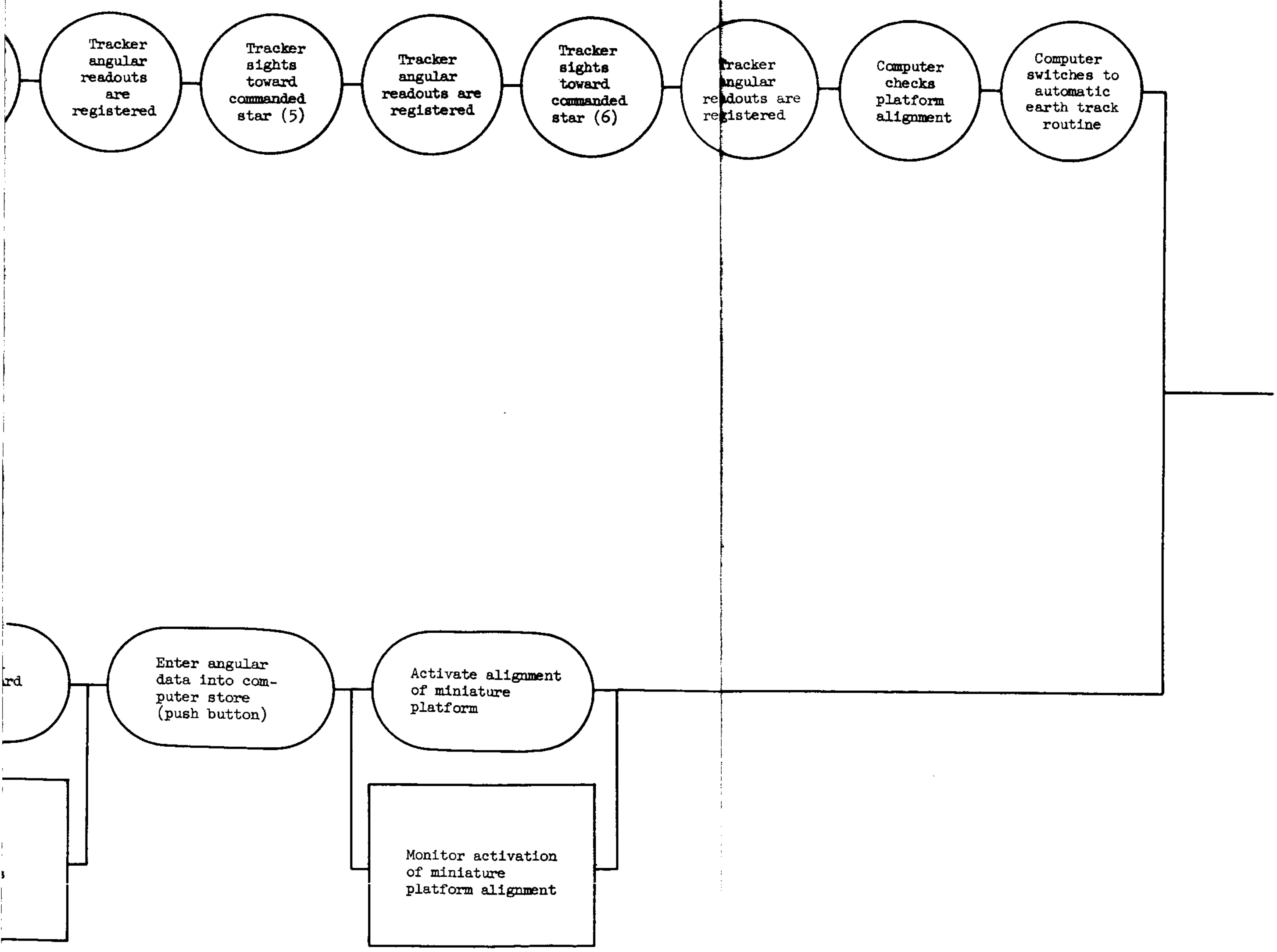
[redacted]


Remove pressure suits
Open passage to mission module
Clean and store pressure suits
T_L = 2 hrs (approx)
Request attitude data from computer, in order to align star tracker with stars to be measured
Computer displays attitude information
Point 3

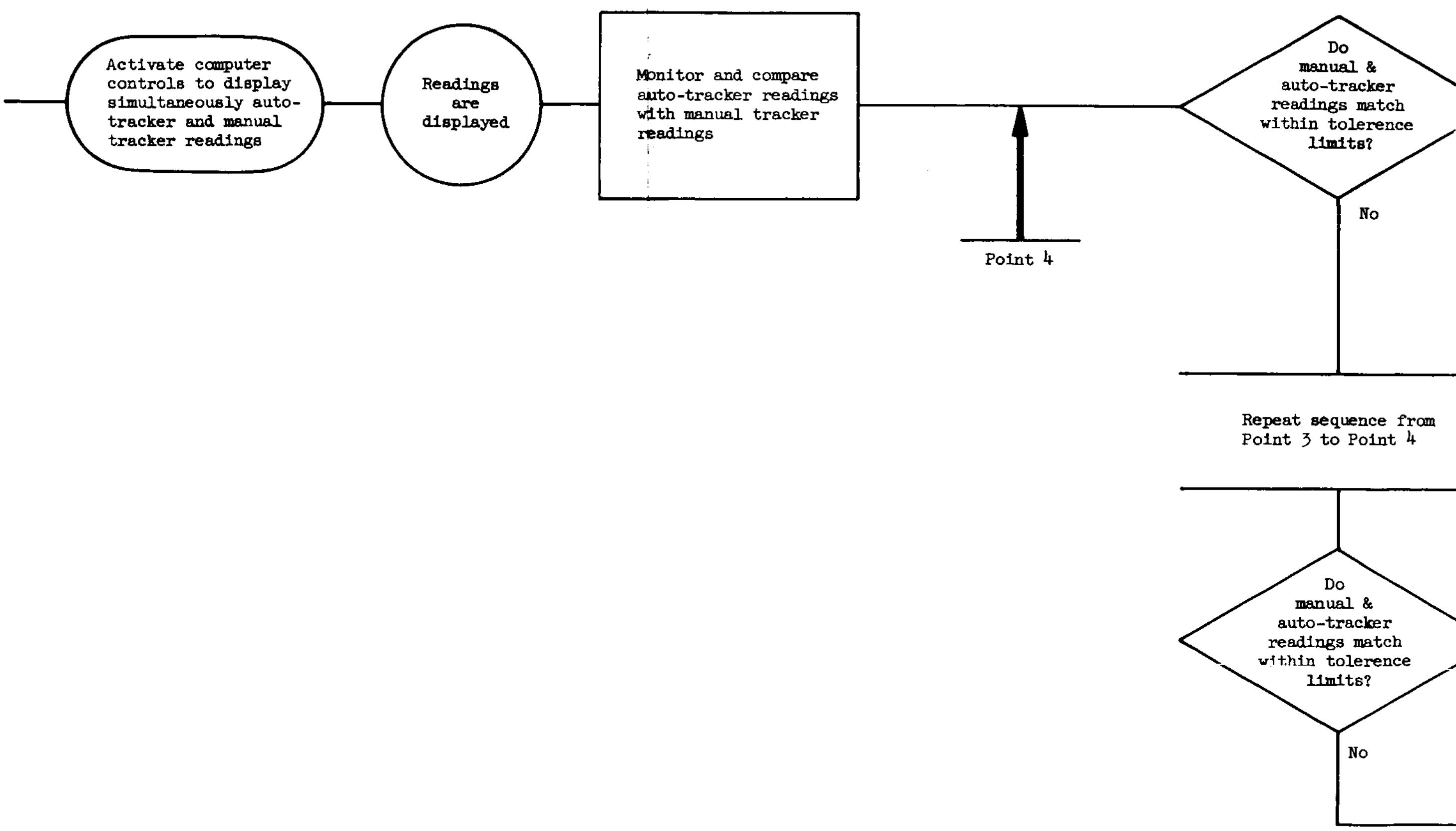


Tracker sights toward commanded star (1)
Tracker angular readouts are registered
Align vehicle attitude to star reference
Switch on computer automatic star search acquisition routine
Shield removed from astro-tracker windows
Three-axis attitude indicator
Computer readout panel
Sight manual tracker toward star (1)
Star and cross-hairs

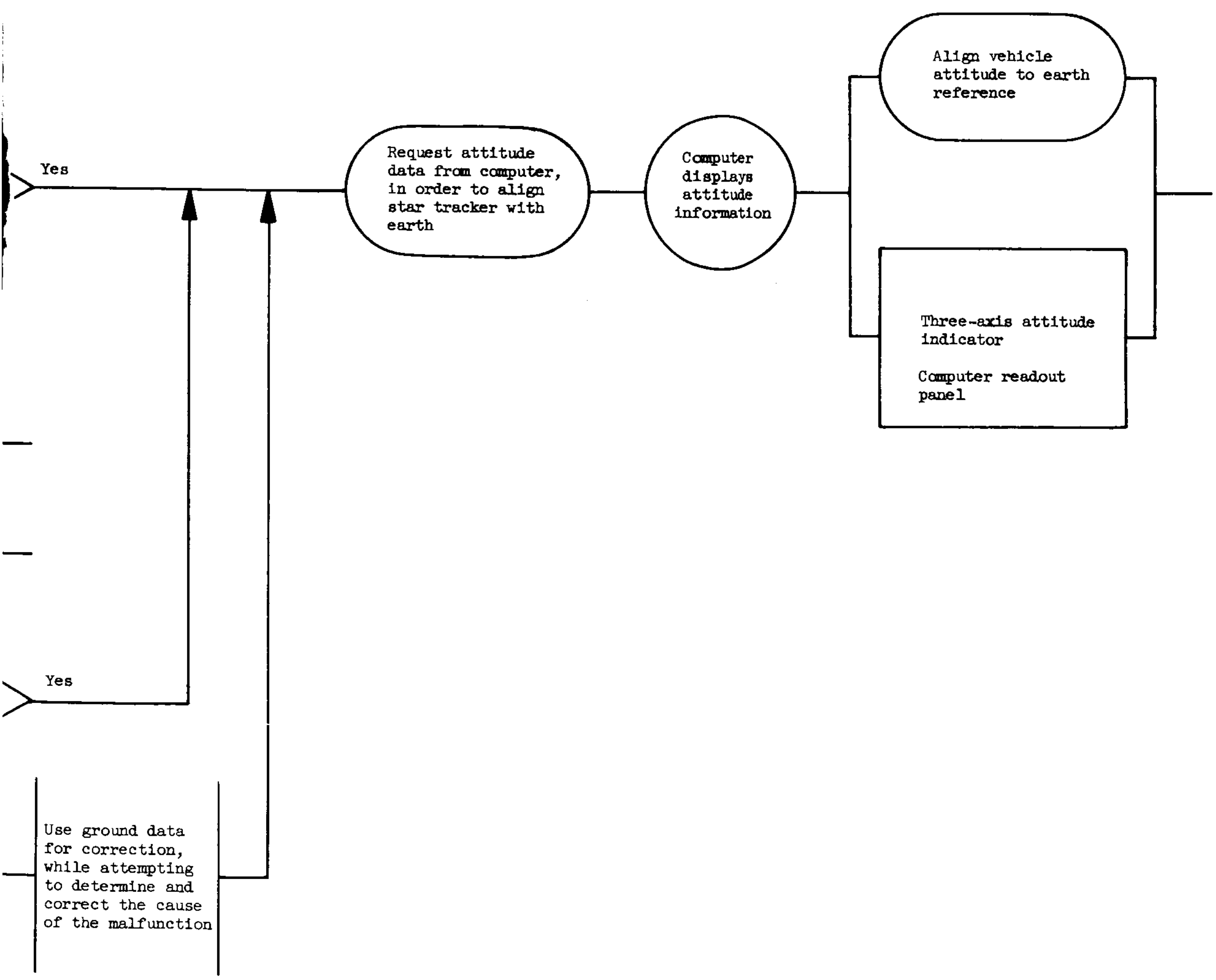

Tracker sights toward commanded star (2)
Tracker angular readouts are registered
Tracker sights toward commanded star (3)
Tracker angular readouts are registered
Platform completes alignment
Tracker sights toward commanded star (4)
Enter angular data into computer store (push button)
Sight manual tracker toward star (2)
Star and cross-hairs
Enter angular data into computer store (push button)
Star and

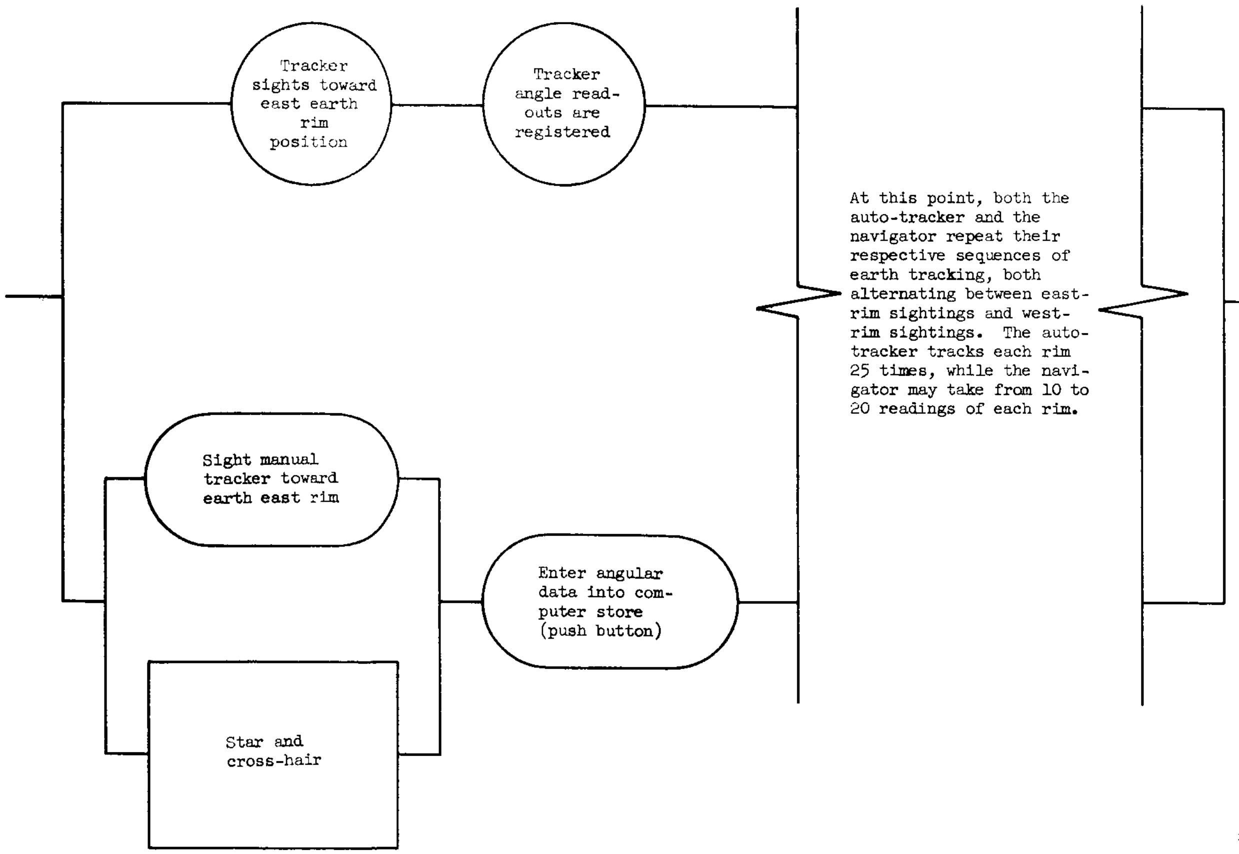

Tracker angular readouts are registered
Tracker sights toward commanded star (5)
Tracker angular readouts are registered
Tracker sights toward commanded star (6)
racker ngular re douts are re istered
Computer checks platform alignment
Computer switches to automatic earth track routine
rd
Enter angular data into computer store (push button)
Activate alignment of miniature platform
Monitor activation of miniature platform alignment

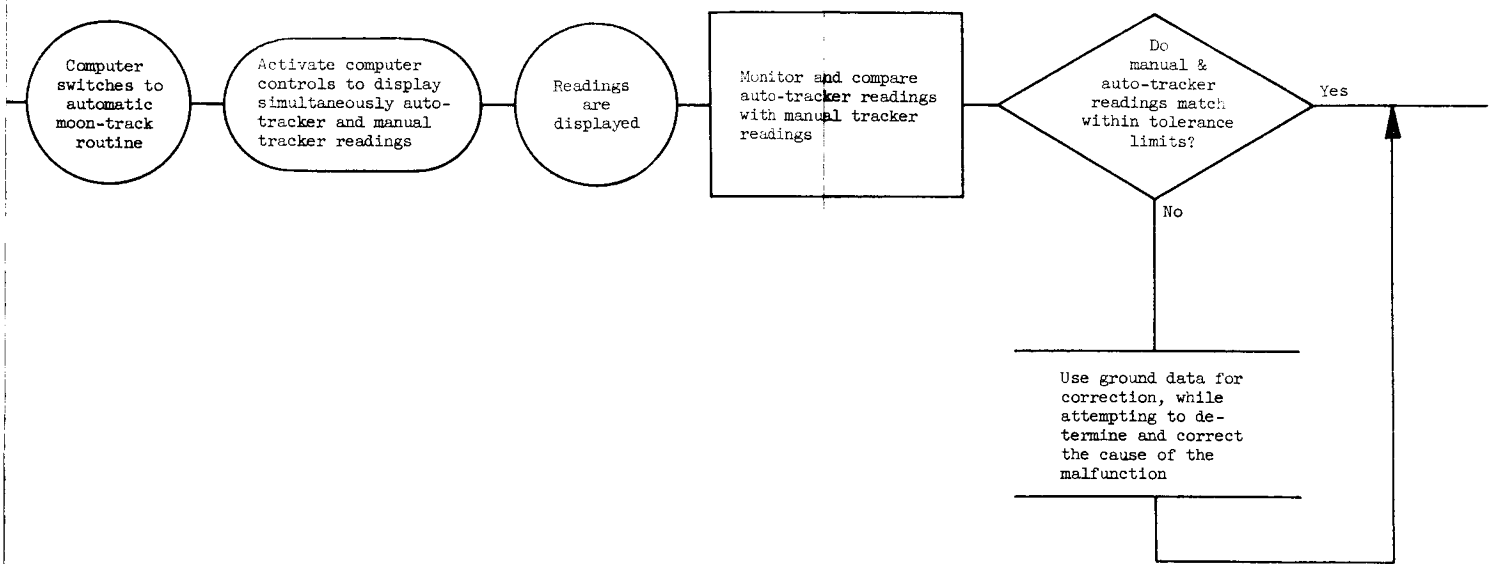
[redacted]



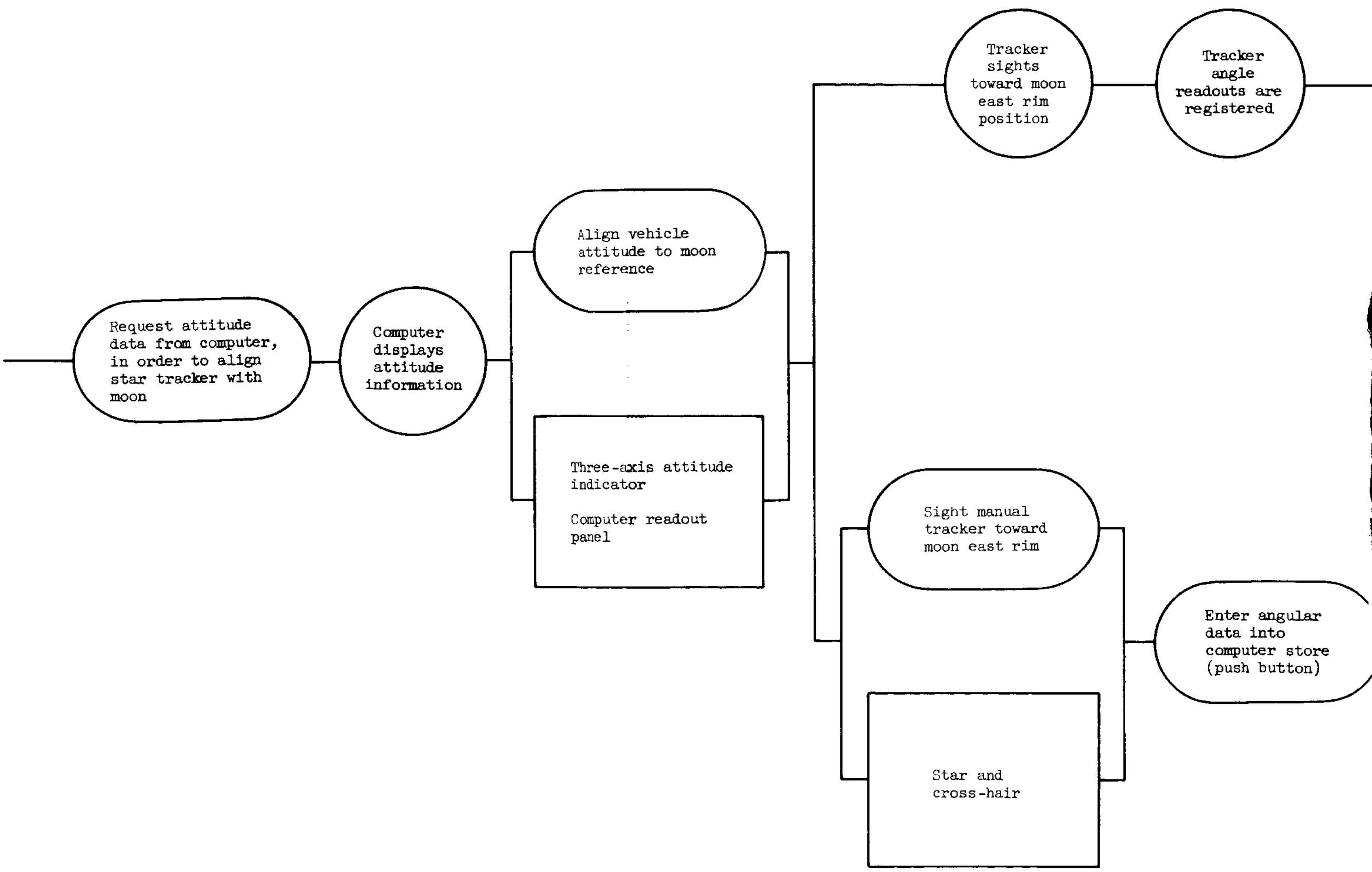
[redacted]


Yes
Request attitude data from computer, in order to align star tracker with earth
Computer displays attitude information
Align vehicle attitude to earth reference
Three-axis attitude indicator
Computer readout panel
Yes
Use ground data for correction, while attempting to determine and correct the cause of the malfunction

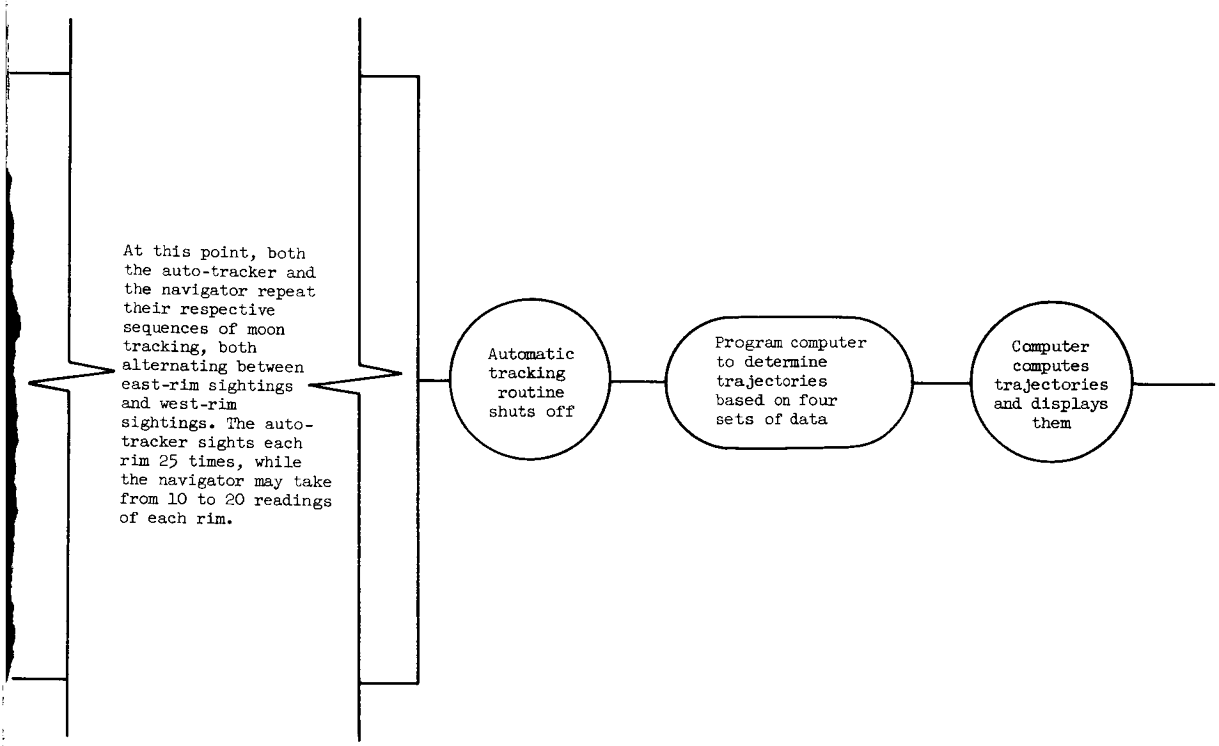

Tracker sights toward east earth rim position
Tracker angle read-outs are registered
At this point, both the auto-tracker and the navigator repeat their respective sequences of earth tracking, both alternating between east-rim sightings and west-rim sightings. The auto-tracker tracks each rim 25 times, while the navigator may take from 10 to 20 readings of each rim.
Sight manual tracker toward earth east rim
Enter angular data into computer store (push button)
Star and cross-hair


Computer switches to automatic moon-track routine
Activate computer controls to display simultaneously auto-tracker and manual tracker readings
Readings are displayed
Monitor and compare auto-tracker readings with manual tracker readings
Do manual & auto-tracker readings match within tolerance limits?
Yes
No
Use ground data for correction, while attempting to determine and correct the cause of the malfunction

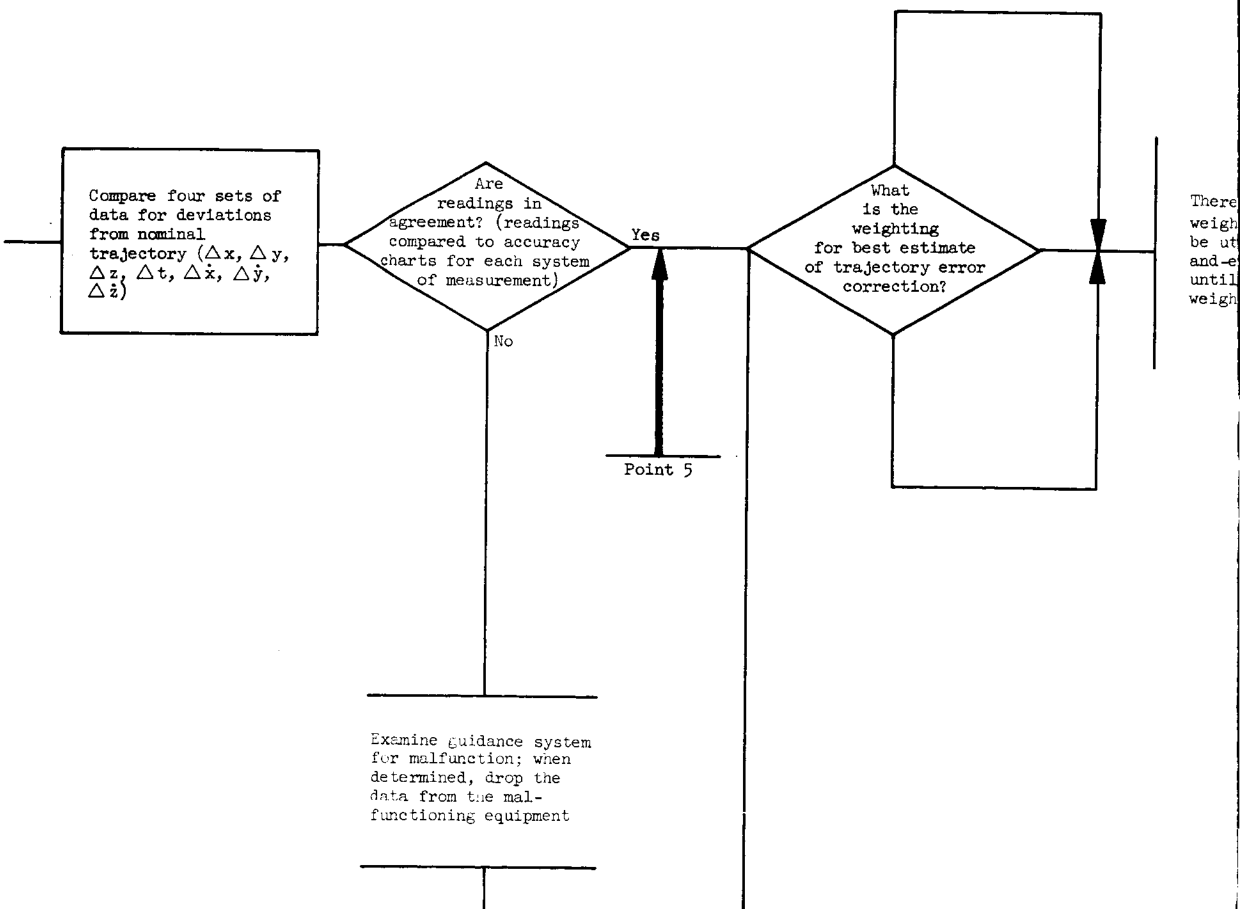
[redacted]



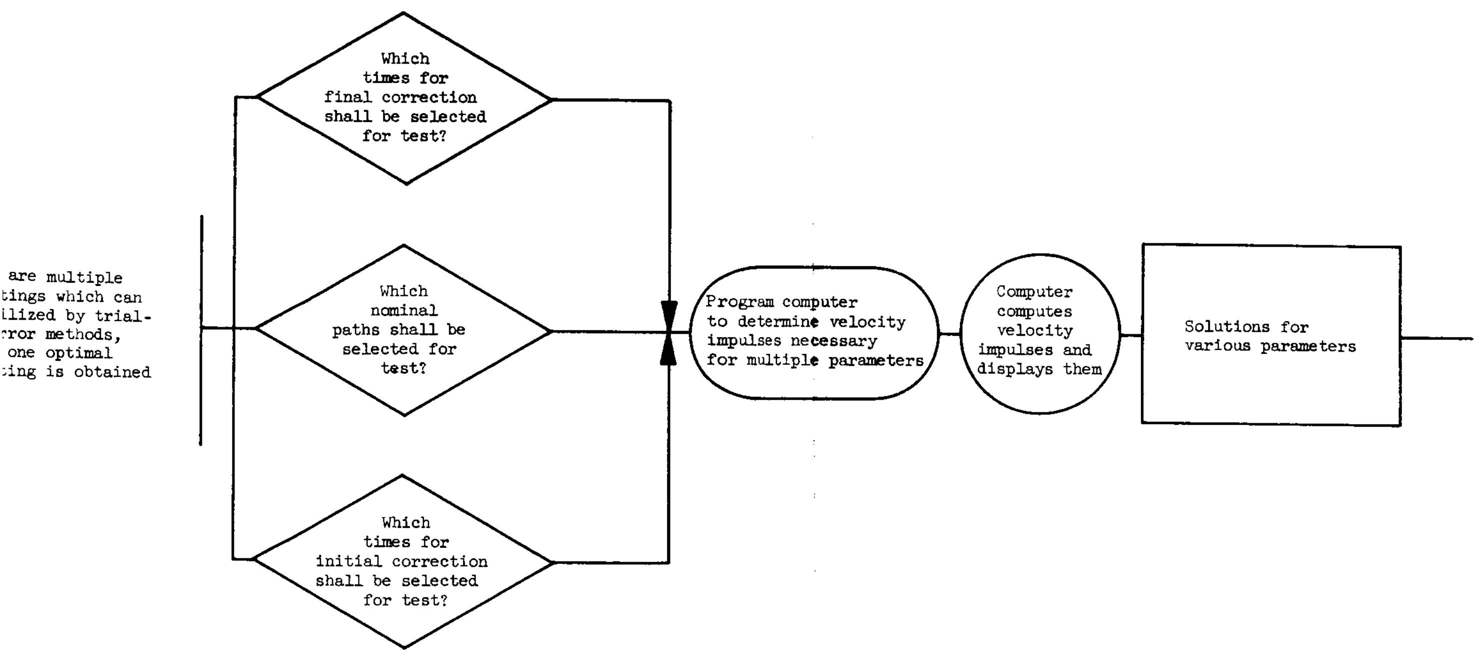
[redacted]

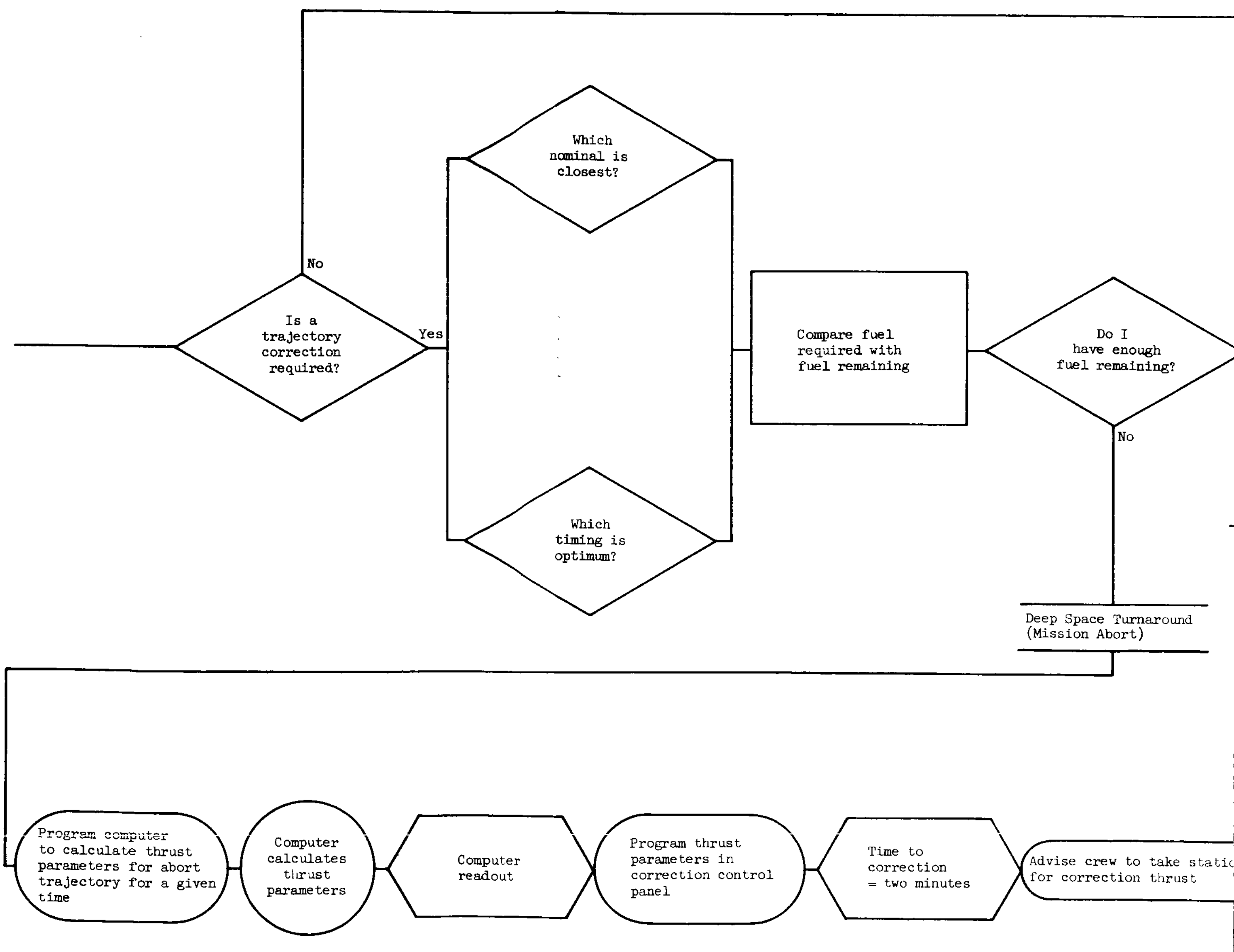


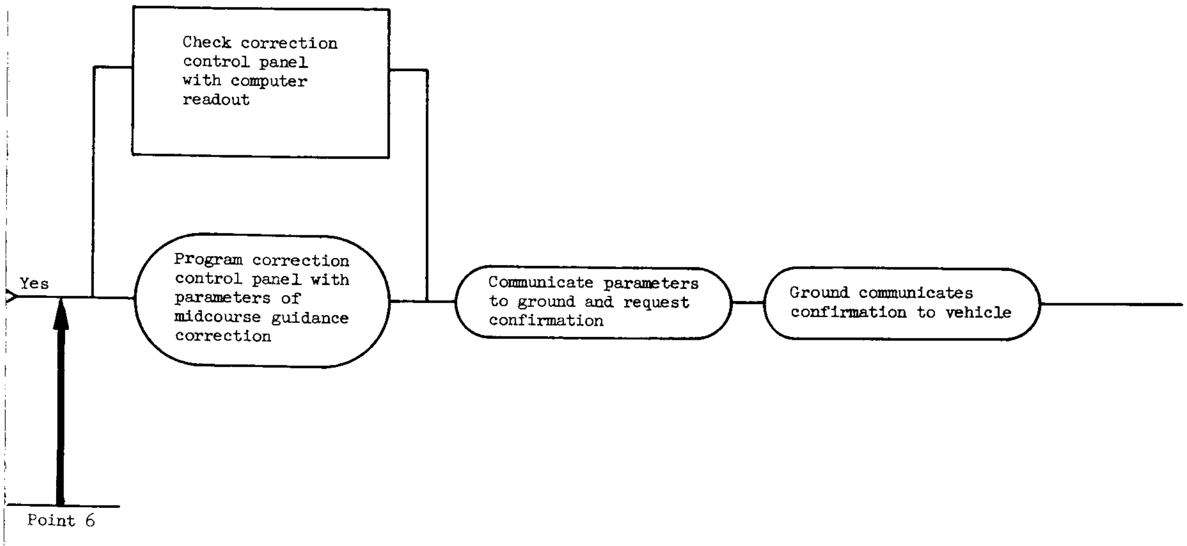
At this point, both the auto-tracker and the navigator repeat their respective sequences of moon tracking, both alternating between east-rim sightings and west-rim sightings. The auto-tracker sights each rim 25 times, while the navigator may take from 10 to 20 readings of each rim.
Automatic tracking routine shuts off
Program computer to determine trajectories based on four sets of data
Computer computes trajectories and displays them

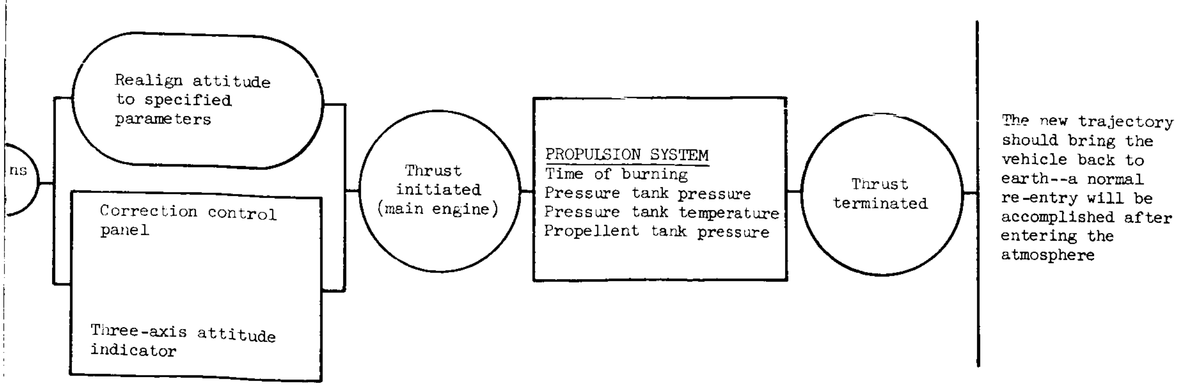


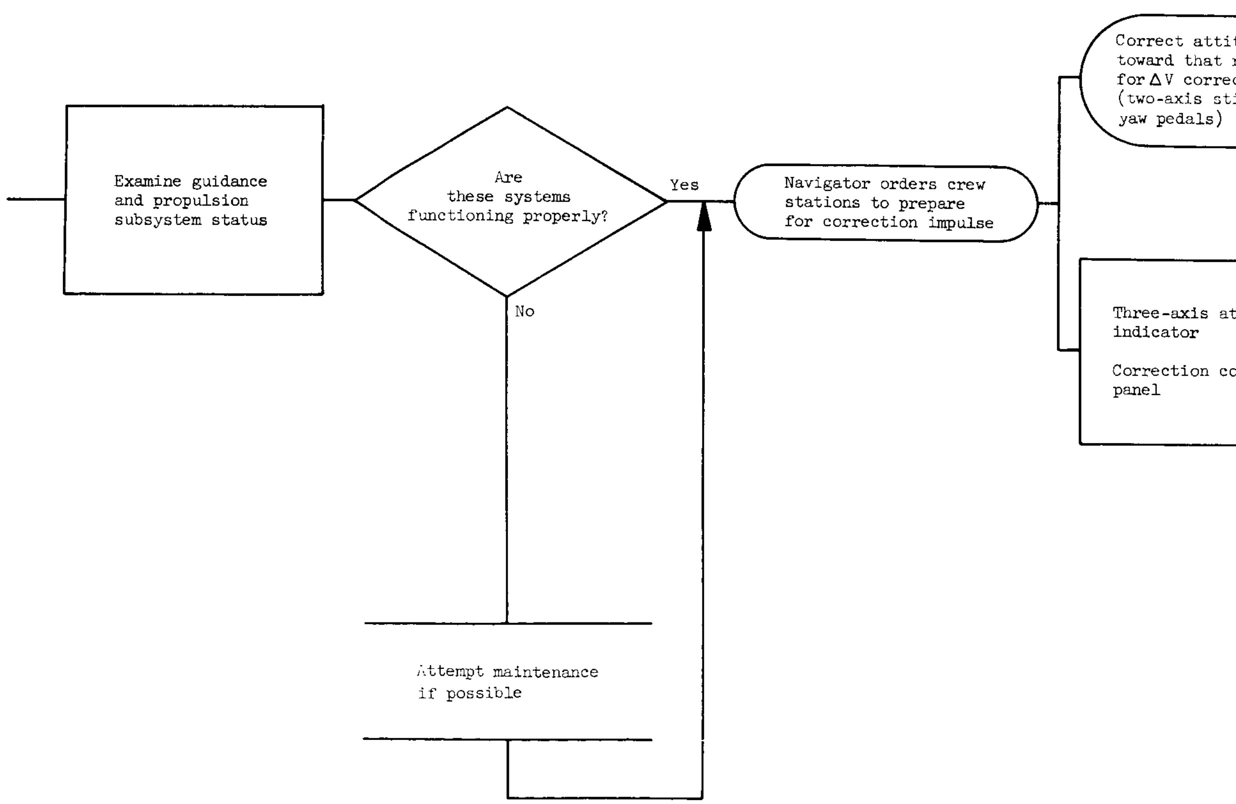
Compare four sets of data for deviations from nominal trajectory (△x, △y, △z, △t, △ẋ, △ẏ, △ż)
Are readings in agreement? (readings compared to accuracy charts for each system of measurement)
Yes
No
Point 5
What is the weighting for best estimate of trajectory error correction?
Examine guidance system for malfunction; when determined, drop the data from the malfunctioning equipment


are multiple
tings which can
ilized by trial-
rror methods,
one optimal
ing is obtained
Which
times for
final correction
shall be selected
for test?
Which
nominal
paths shall be
selected for
test?
Which
times for
initial correction
shall be selected
for test?
Program computer
to determine velocity
impulses necessary
for multiple parameters
Computer
computes
velocity
impulses and
displays them
Solutions for
various parameters

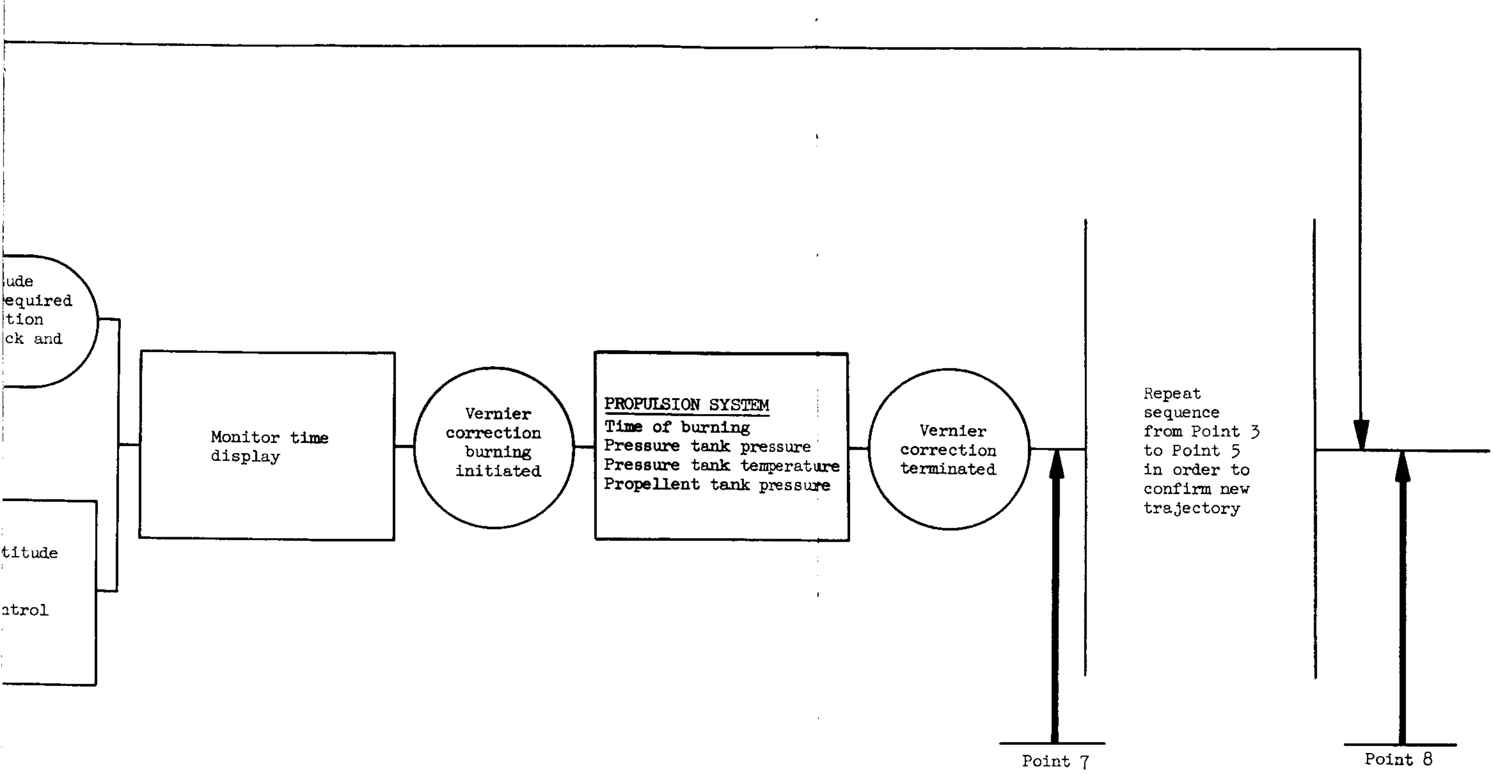

Is a trajectory correction required?
No
Yes
Which nominal is closest?
Which timing is optimum?
Compare fuel required with fuel remaining
Do I have enough fuel remaining?
No
Deep Space Turnaround (Mission Abort)
Program computer to calculate thrust parameters for abort trajectory for a given time
Computer calculates thrust parameters
Computer readout
Program thrust parameters in correction control panel
Time to correction = two minutes
Advise crew to take statio
for correction thrust


Check correction control panel with computer readout
Yes
Program correction control panel with parameters of midcourse guidance correction
Communicate parameters to ground and request confirmation
Ground communicates confirmation to vehicle
Point 6

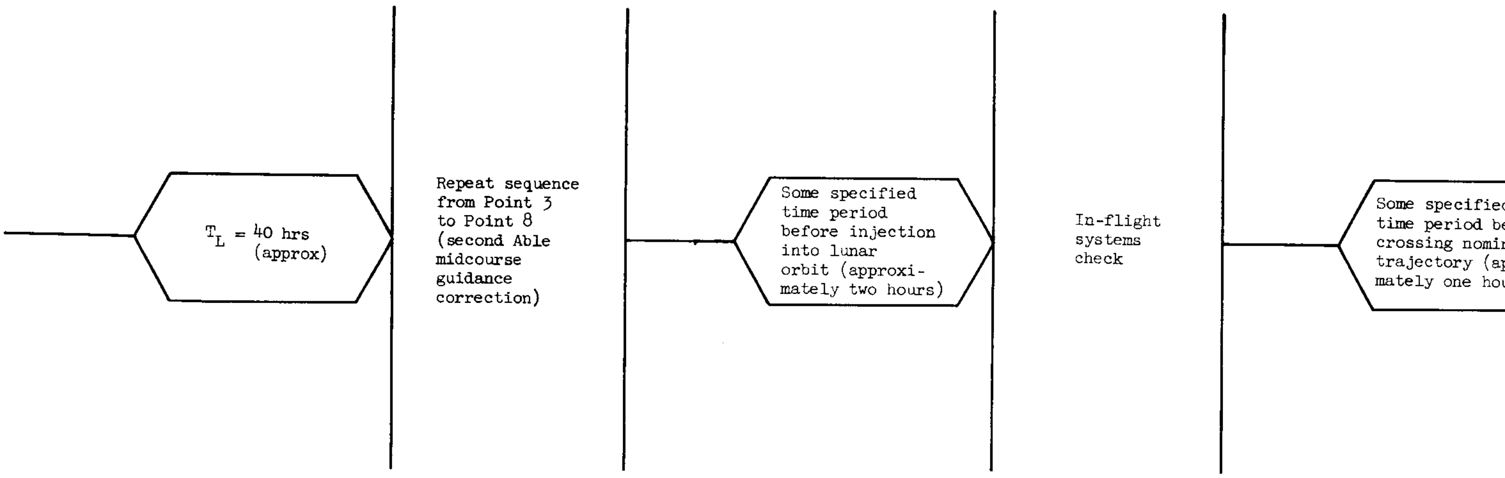

ns
Realign attitude to specified parameters
Correction control panel
Three-axis attitude indicator
Thrust initiated (main engine)
PROPULSION SYSTEM
Time of burning
Pressure tank pressure
Pressure tank temperature
Propellent tank pressure
Thrust terminated
The new trajectory should bring the vehicle back to earth--a normal re-entry will be accomplished after entering the atmosphere


Examine guidance and propulsion subsystem status
Are these systems functioning properly?
Yes
No
Navigator orders crew stations to prepare for correction impulse
Attempt maintenance if possible
Correct atti
toward that
for ΔV corre
(two-axis st
yaw pedals)
Three-axis at
indicator
Correction co
panel

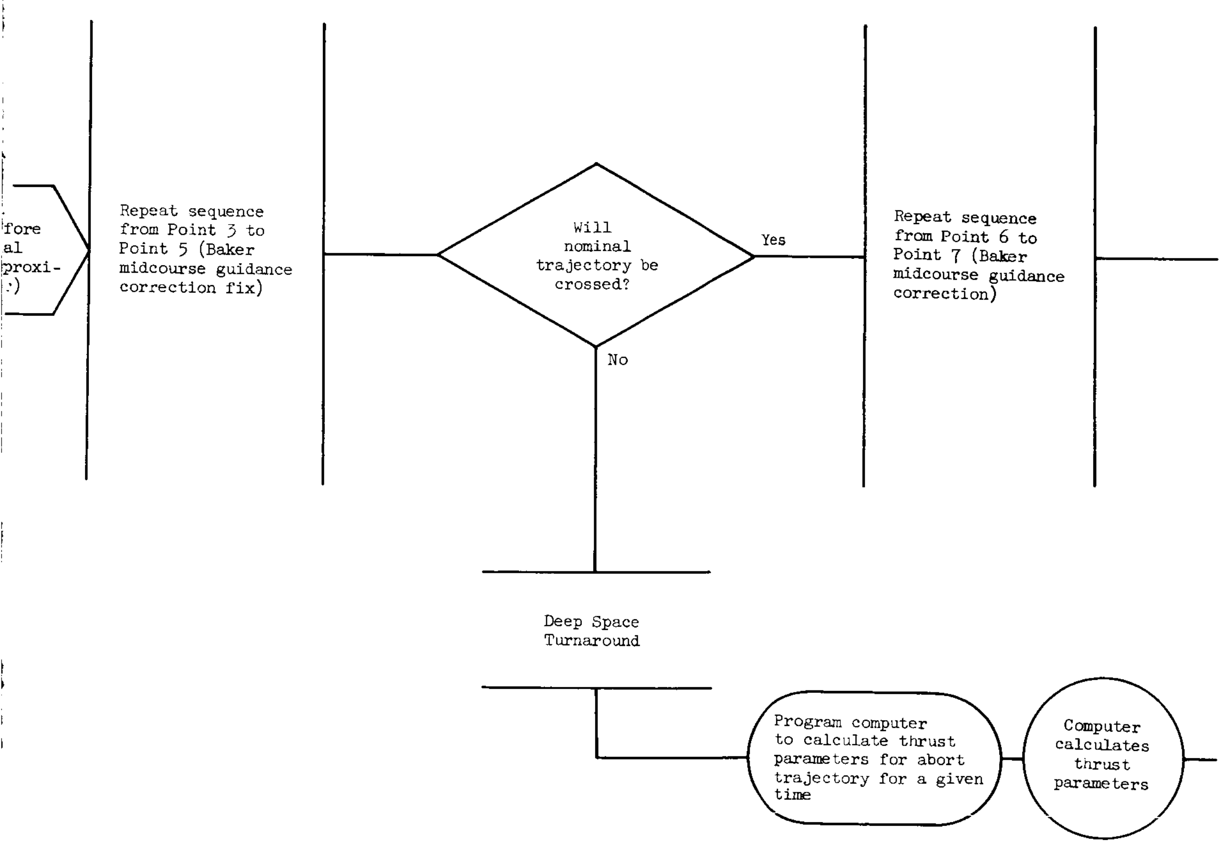
E

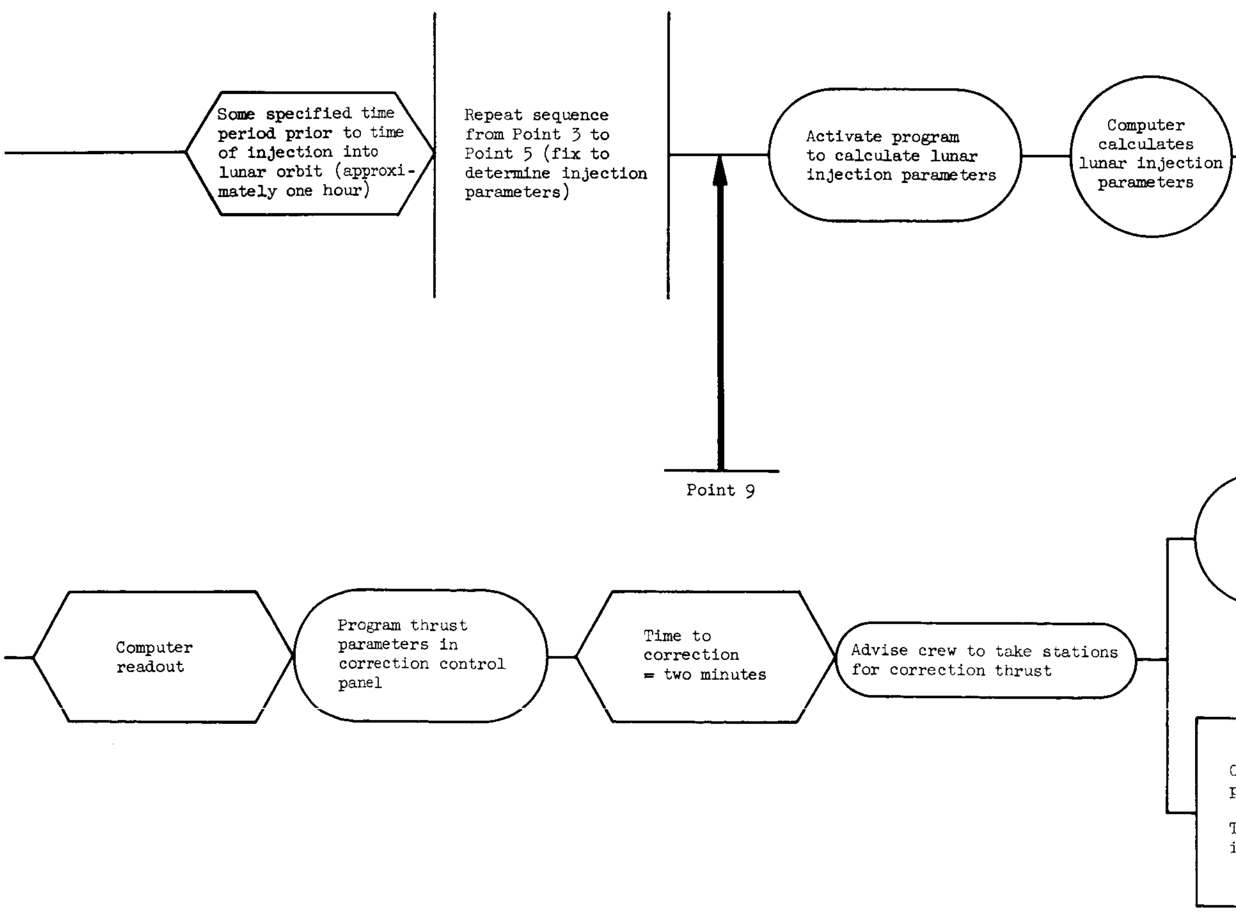

ude
equired
tion
ck and
titude
ntrol
Monitor time display
Vernier correction burning initiated
PROPULSION SYSTEM
Time of burning
Pressure tank pressure
Pressure tank temperature
Propellent tank pressure
Vernier correction terminated
Repeat sequence from Point 3 to Point 5 in order to confirm new trajectory
Point 7
Point 8

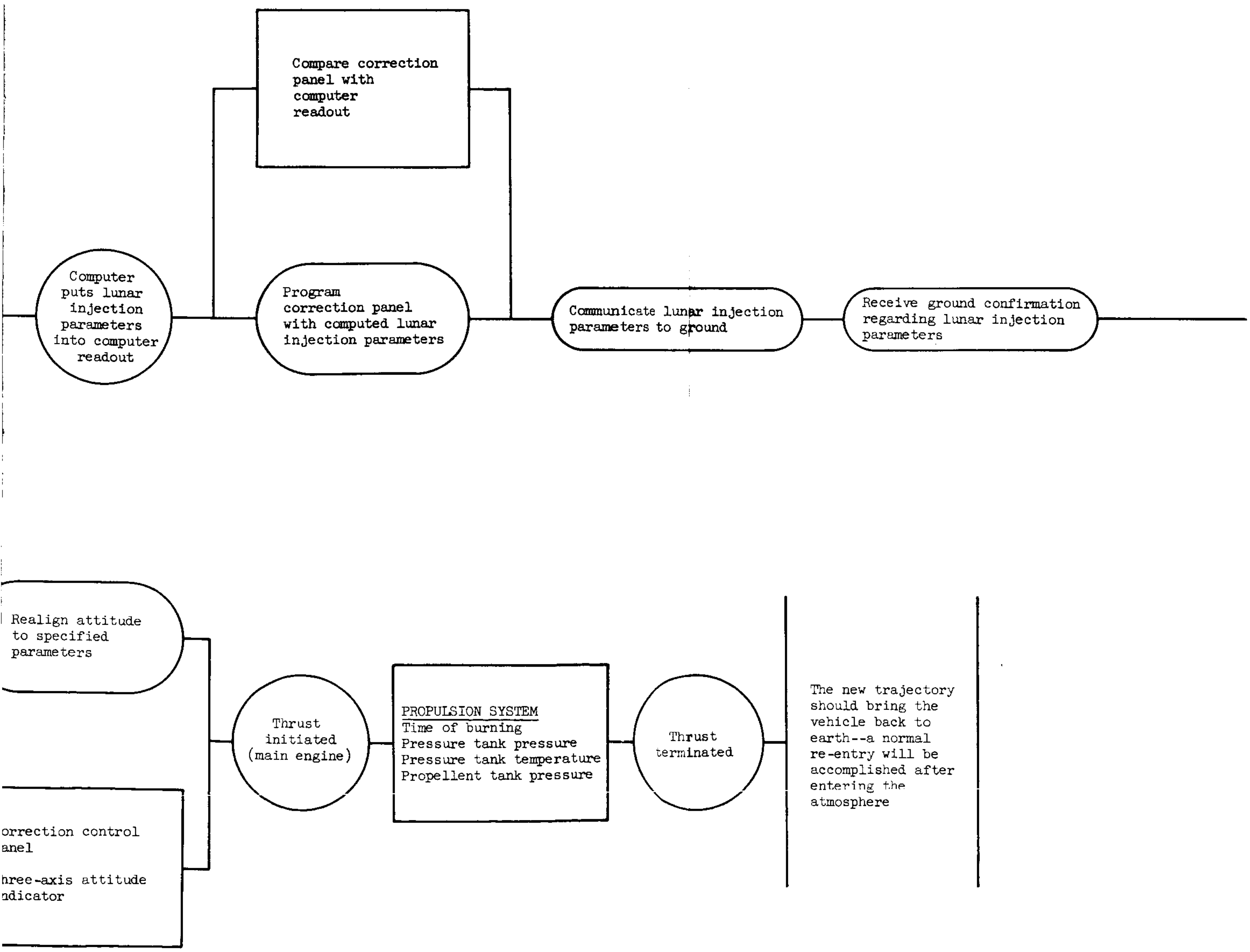
[redacted]



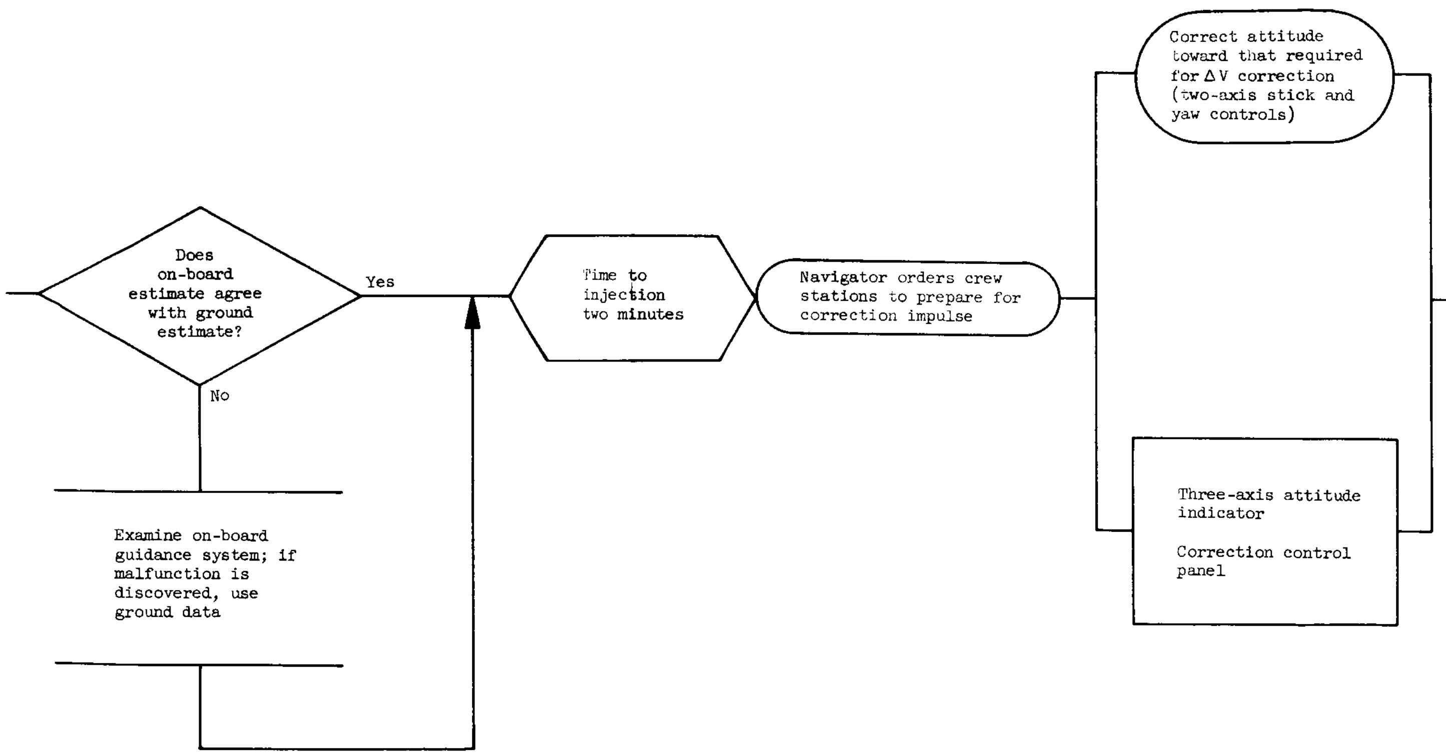
[redacted]


fore
al
proxi-
·)
Repeat sequence from Point 3 to Point 5 (Baker midcourse guidance correction fix)
Will nominal trajectory be crossed?
Yes
No
Repeat sequence from Point 6 to Point 7 (Baker midcourse guidance correction)
Deep Space Turnaround
Program computer to calculate thrust parameters for abort trajectory for a given time
Computer calculates thrust parameters

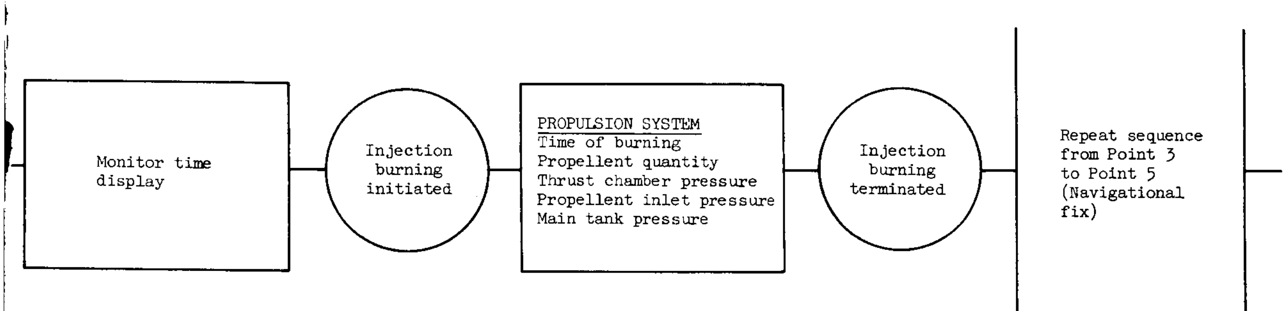

Some specified time period prior to time of injection into lunar orbit (approximately one hour)
Repeat sequence from Point 3 to Point 5 (fix to determine injection parameters)
Activate program to calculate lunar injection parameters
Computer calculates lunar injection parameters
Point 9
Computer readout
Program thrust parameters in correction control panel
Time to correction = two minutes
Advise crew to take stations for correction thrust

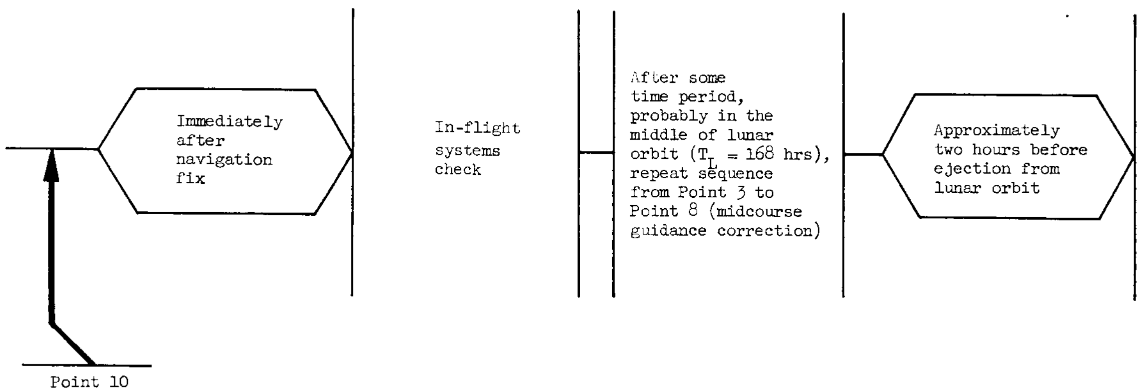

Compare correction panel with computer readout
Computer puts lunar injection parameters into computer readout
Program correction panel with computed lunar injection parameters
Communicate lunar injection parameters to ground
Receive ground confirmation regarding lunar injection parameters
Realign attitude to specified parameters
orrection control anel
hree-axis attitude ndicator
Thrust initiated (main engine)
PROPULSION SYSTEM
Time of burning
Pressure tank pressure
Pressure tank temperature
Propellent tank pressure
Thrust terminated
The new trajectory should bring the vehicle back to earth--a normal re-entry will be accomplished after entering the atmosphere

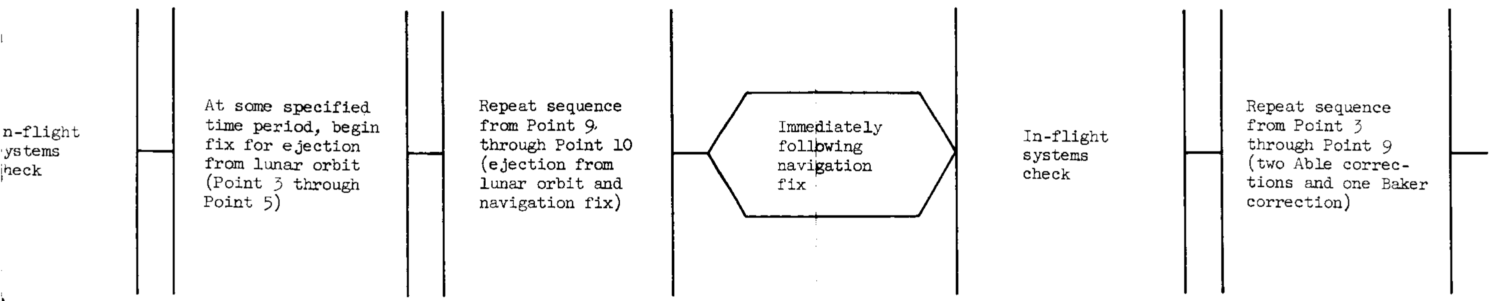
[redacted]

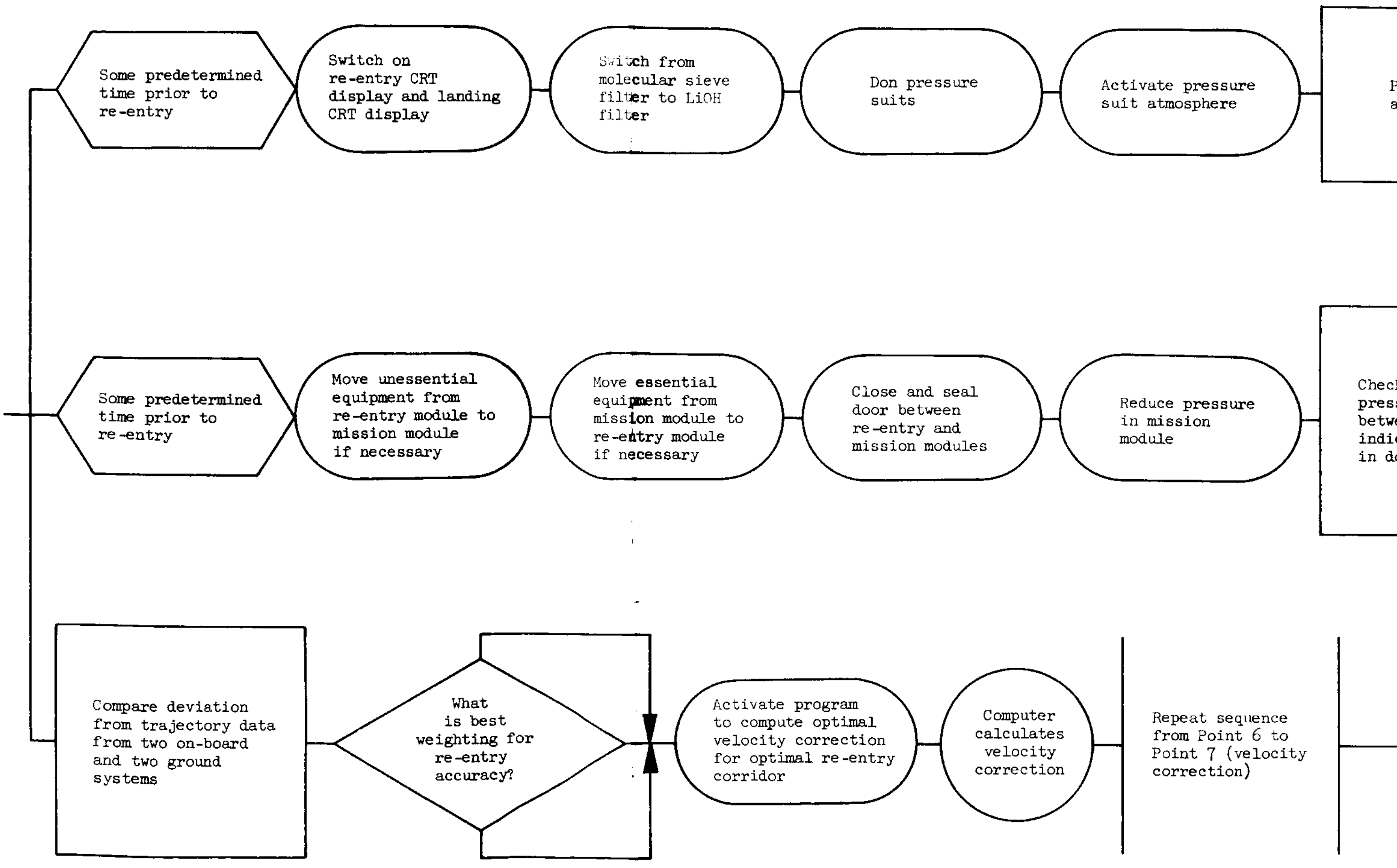


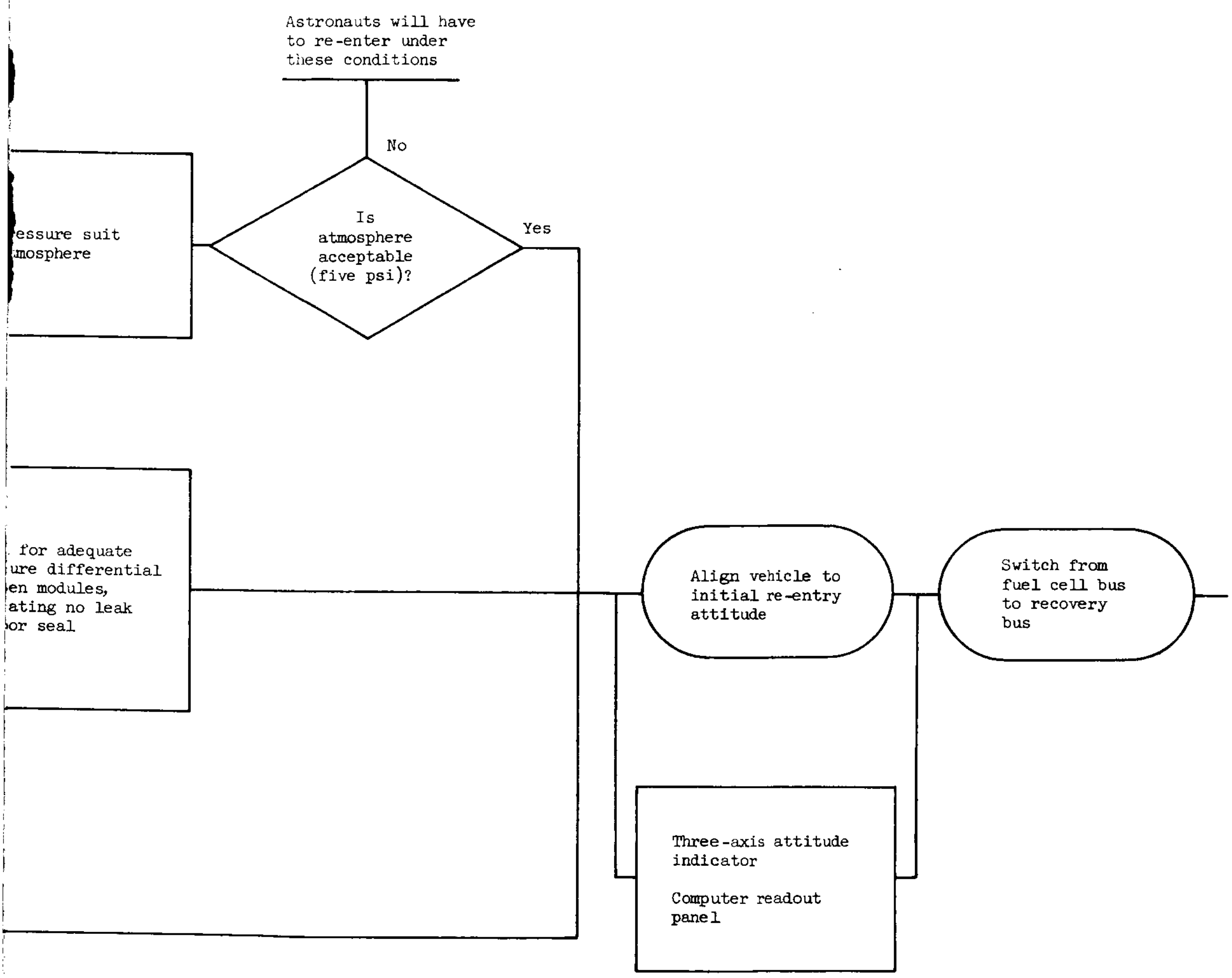
[redacted]

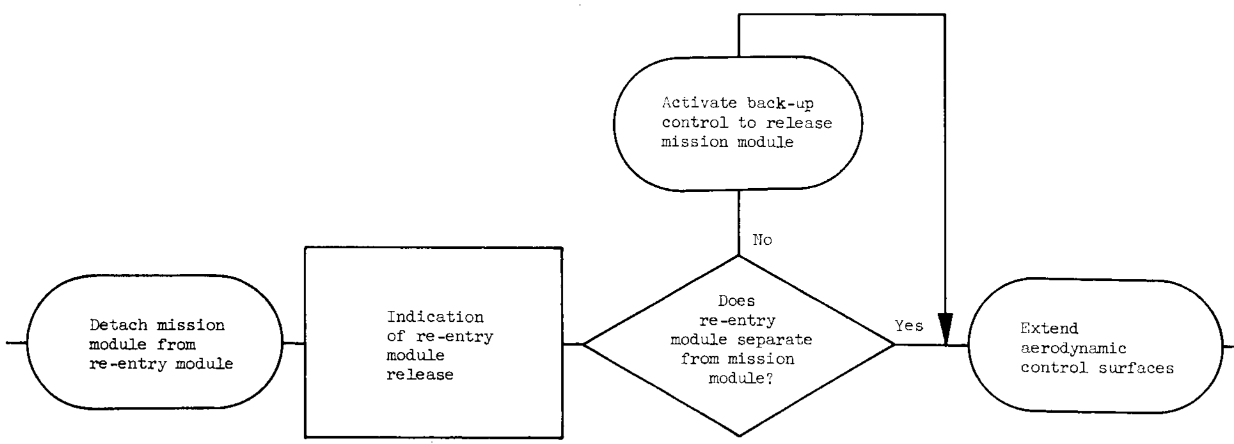

Monitor time display
Injection burning initiated
PROPULSION SYSTEM
Time of burning
Propellent quantity
Thrust chamber pressure
Propellent inlet pressure
Main tank pressure
Injection burning terminated
Repeat sequence from Point 3 to Point 5 (Navigational fix)

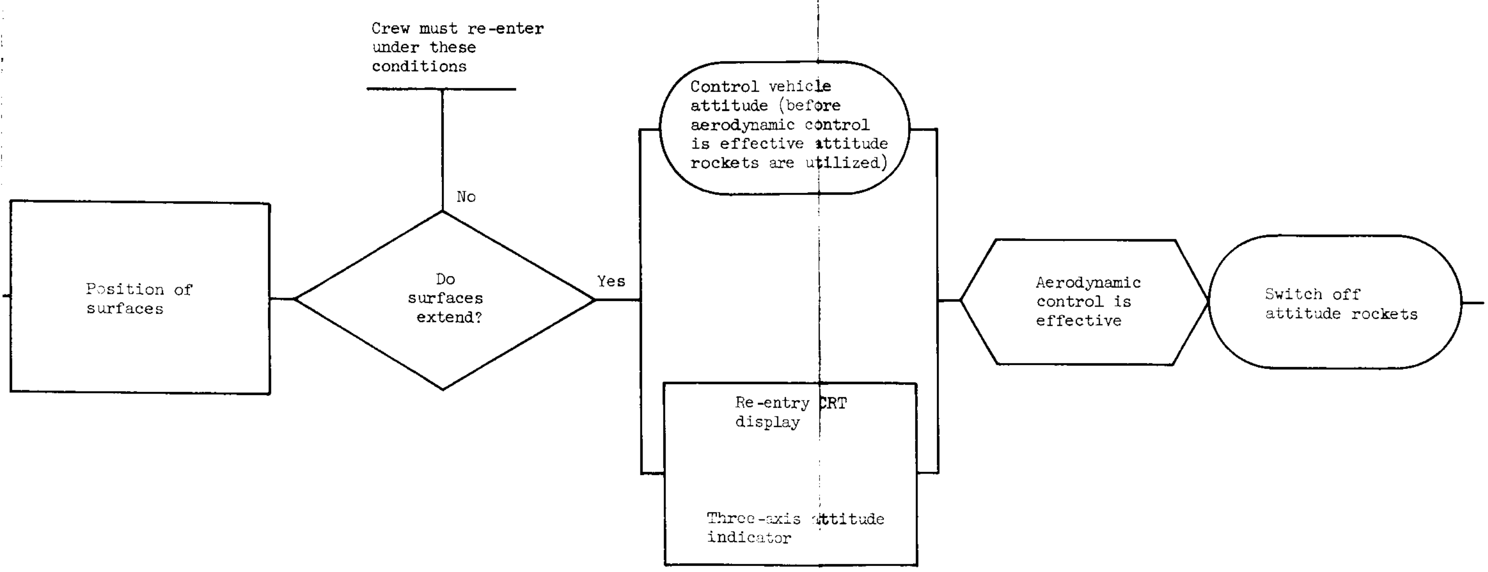

Immediately after navigation fix
In-flight systems check
After some time period, probably in the middle of lunar orbit (T_L = 168 hrs), repeat sequence from Point 3 to Point 8 (midcourse guidance correction)
Approximately two hours before ejection from lunar orbit
Point 10


n-flight
ystems
heck
At some specified time period, begin fix for ejection from lunar orbit (Point 3 through Point 5)
Repeat sequence from Point 9 through Point 10 (ejection from lunar orbit and navigation fix)
Immediately following navigation fix
In-flight systems check
Repeat sequence from Point 3 through Point 9 (two Able corrections and one Baker correction)

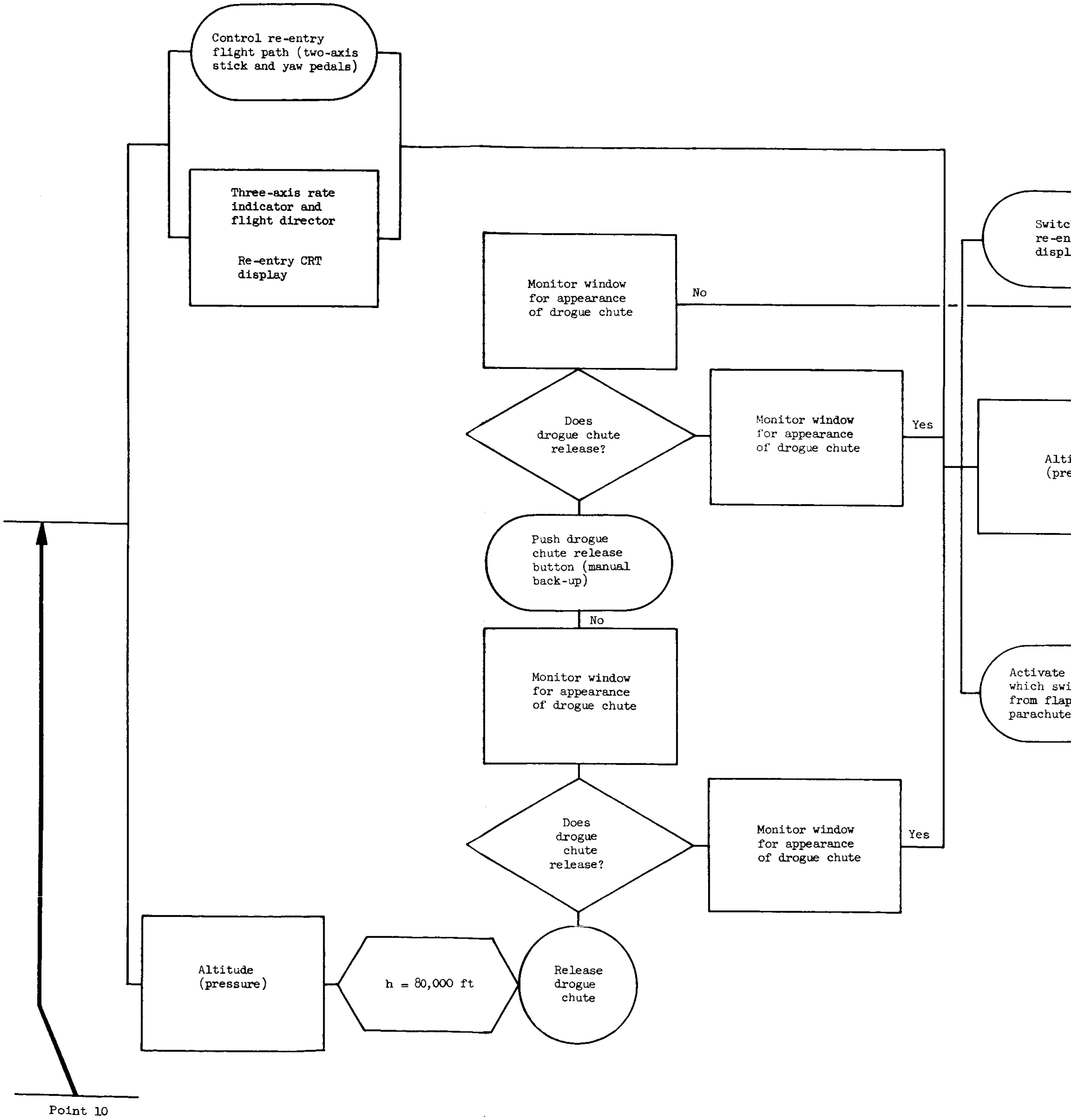

Some predetermined time prior to re-entry
Switch on re-entry CRT display and landing CRT display
Switch from molecular sieve filter to LiOH filter
Don pressure suits
Activate pressure suit atmosphere
Some predetermined time prior to re-entry
Move unessential equipment from re-entry module to mission module if necessary
Move essential equipment from mission module to re-entry module if necessary
Close and seal door between re-entry and mission modules
Reduce pressure in mission module
Compare deviation from trajectory data from two on-board and two ground systems
What is best weighting for re-entry accuracy?
Activate program to compute optimal velocity correction for optimal re-entry corridor
Computer calculates velocity correction
Repeat sequence from Point 6 to Point 7 (velocity correction)


Astronauts will have to re-enter under these conditions
No
essure suit
mosphere
Is atmosphere acceptable (five psi)?
Yes
for adequate
ure differential
en modules,
ating no leak
or seal
Align vehicle to initial re-entry attitude
Switch from fuel cell bus to recovery bus
Three-axis attitude indicator
Computer readout panel

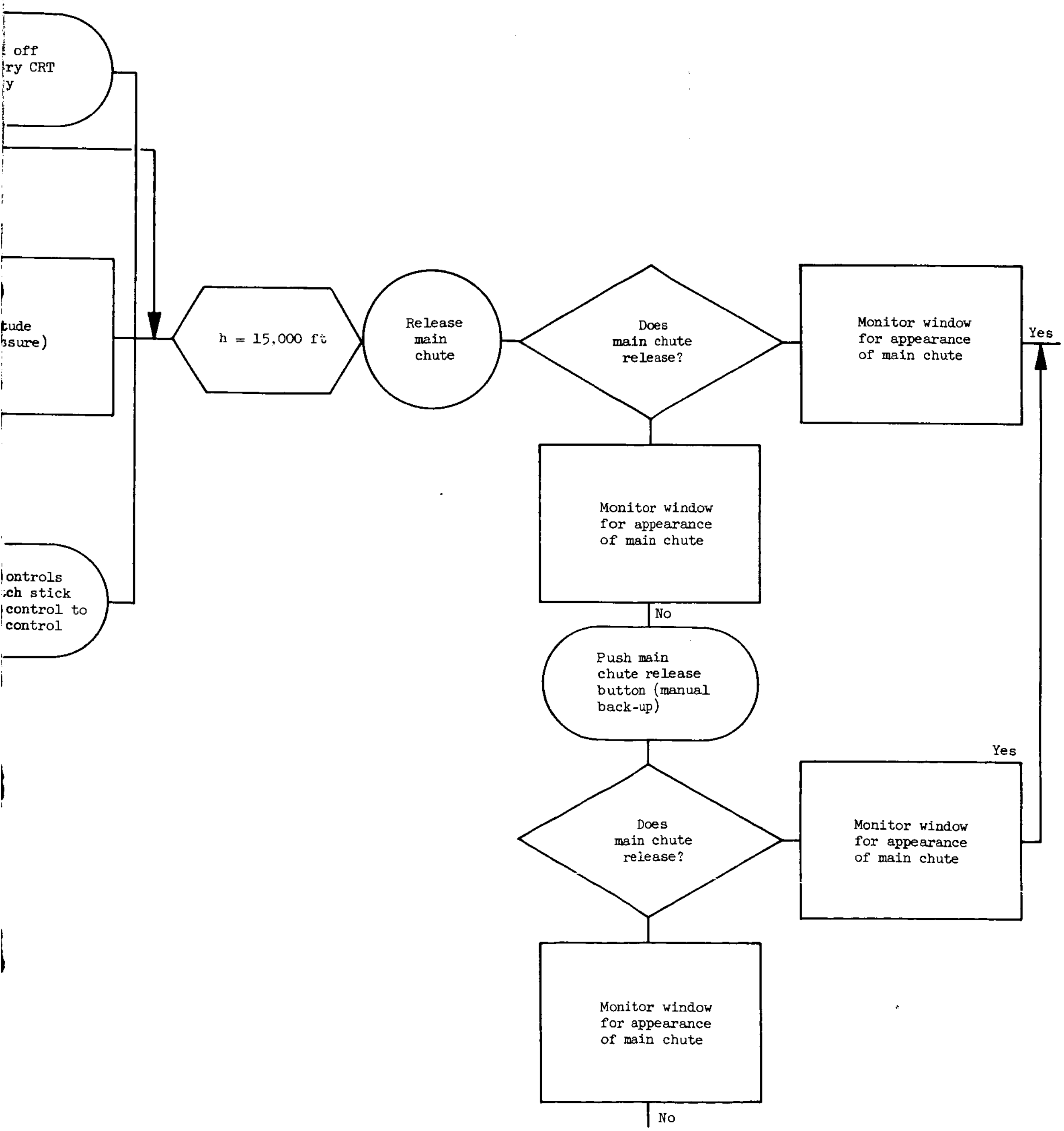

Detach mission module from re-entry module
Indication of re-entry module release
Does re-entry module separate from mission module?
No
Activate back-up control to release mission module
Yes
Extend aerodynamic control surfaces

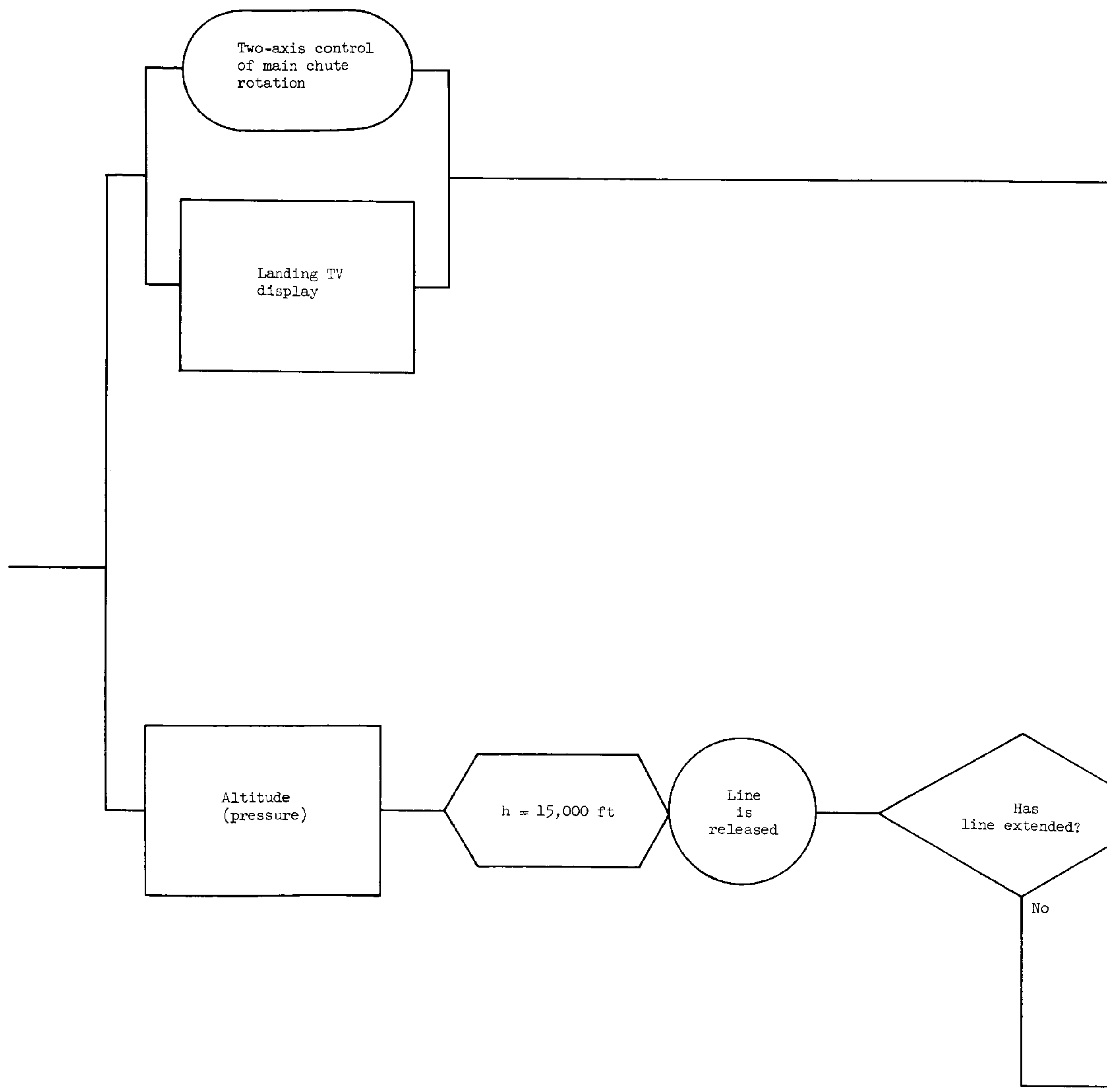

Crew must re-enter under these conditions
No
Position of surfaces
Do surfaces extend?
Yes
Control vehicle attitude (before aerodynamic control is effective attitude rockets are utilized)
Re-entry CRT display
Three-axis attitude indicator
Aerodynamic control is effective
Switch off attitude rockets

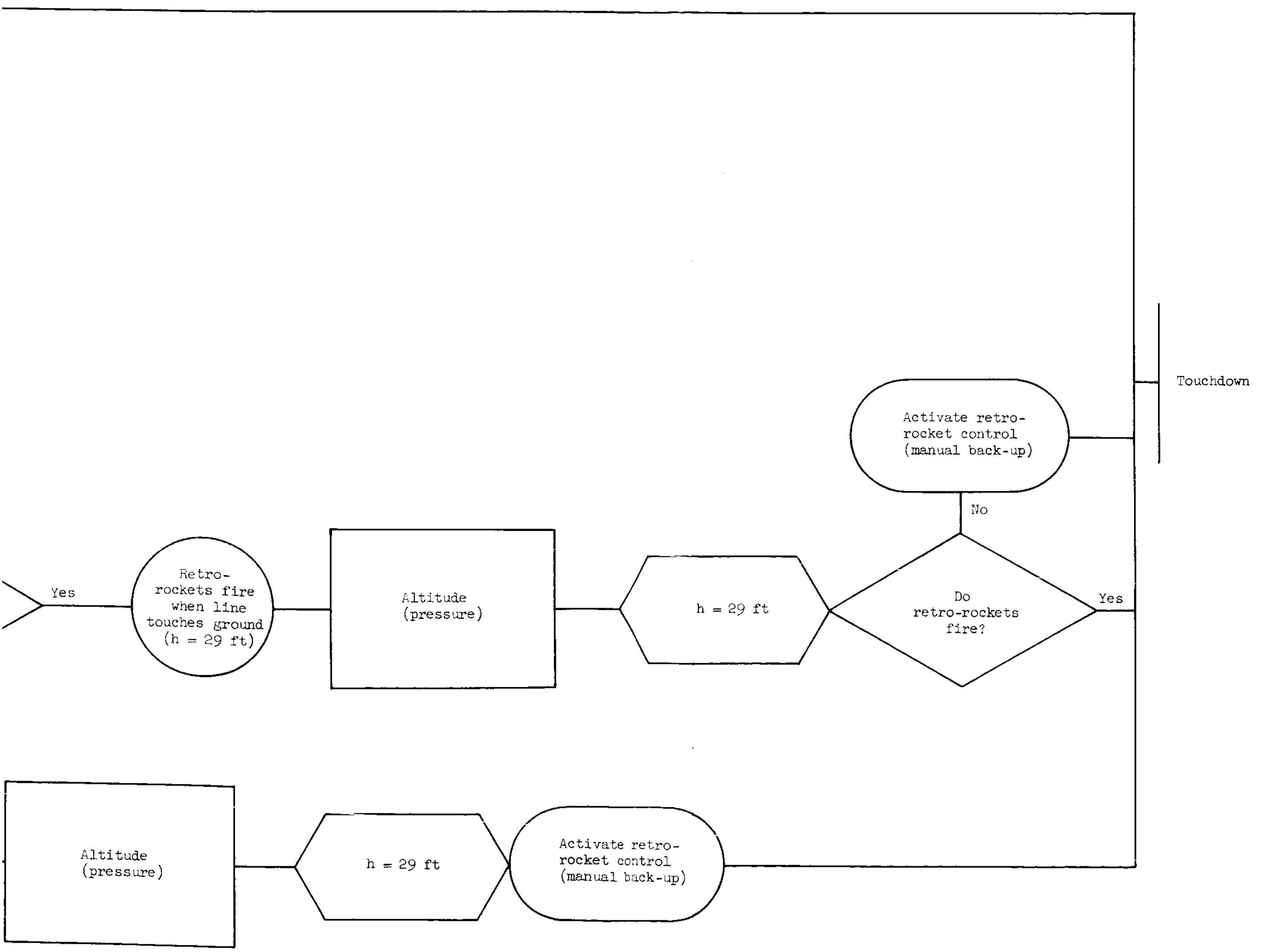
CONFIDENTI



Control re-entry flight path (two-axis stick and yaw pedals)
Three-axis rate indicator and flight director
Re-entry CRT display
Monitor window for appearance of drogue chute
No
Switc re-en displ
Does drogue chute release?
Monitor window for appearance of drogue chute
Yes
Alti (pre
Push drogue chute release button (manual back-up)
No
Monitor window for appearance of drogue chute
Activate which swi from flap parachute
Does drogue chute release?
Monitor window for appearance of drogue chute
Yes
Altitude (pressure)
h = 80,000 ft
Release drogue chute
Point 10


off
ry CRT
y
tude
ssure)
ontrols
ch stick
control to
control
h = 15,000 ft
Release main chute
Does main chute release?
Monitor window for appearance of main chute
Yes
Monitor window for appearance of main chute
No
Push main chute release button (manual back-up)
Yes
Does main chute release?
Monitor window for appearance of main chute
Monitor window for appearance of main chute
No


Two-axis control of main chute rotation
Landing TV display
Altitude (pressure)
h = 15,000 ft
Line is released
Has line extended?
No


Touchdown
Activate retro-
rocket control
(manual back-up)
No
Yes
Retro-
rockets fire
when line
touches ground
(h = 29 ft)
Altitude
(pressure)
h = 29 ft
Do
retro-rockets
fire?
Yes
Altitude
(pressure)
h = 29 ft
Activate retro-
rocket control
(manual back-up)

d. Results of analysis

In setting up the flow diagram each system was reviewed with the various engineers, in an attempt to determine what man's greatest contributions to the Apollo would be. Thus, the system was essentially built about man, so that the vehicle design would take full advantage of those unique talents which man could offer. If a listing were made of those abilities possessed by man, which could be utilized within the Apollo system, the most significant of these would be as follows:

(1) Information processing abilities

(2) Decision-making abilities

(3) Continuous psychomotor abilities

(4) Discreet psychomotor abilities

(5) Trouble-shooting and maintenance abilities

Operational definitions of these are as follows:

(1) Information-processing--Consists of detection and discrimination of specific information from the total available to the human, processing storing and later possibly transmitting this information.

(2) Decision-making--The process whereby the human chooses, from a set of possible acts, those which he feels maximize (or minimize) a given index.

(3) Continuous psychomotor activity--Behavior which involves the control of proprioceptive responses based on the utilization of stored information over an extended period of time.

(4) Discreet psychomotor activity--Behavior which involves the control of proprioceptive responses based on the utilization of stored information over a short interval of time.

(5) Troubleshooting and maintenance--This is the process whereby a human must detect some characteristic of equipment which should not normally exist, isolate the reason for this condition, and remedy the cause of the malfunctioning equipment.

Upon examination of the sequential flow chart it was determined that in almost every case, information was processed by the crew members for the purpose of gaining data in order to make a decision. Thus, in order not to disrupt the integrity of the analysis, both of those functions will be discussed in one single portion of the report, and those information-processing activities not directly affecting a decision will be discussed as exceptions to the rule.

Information-processing: decision-making. Throughout the duration of a lunar mission, there will be a continuous task of monitoring 30 information channels. The purpose of this monitoring behavior is to detect an equipment malfunction. The information channels listed should give him indications of complete operational systems status, with the exception of the propulsion system, which can only be examined fully while it is actually burning. It will also be necessary for the member of the crew doing the monitoring to chart certain system information at discrete time intervals in order to get long-term (i.e., over a period of hours or days) rate information. An example of this is the measurement of oxygen and hydrogen levels for the main vehicle propulsion system. The only time these quantities can be measured in deep space is while under an acceleration load (using vernier engines). However, rates-of-boiloff of these fuels are critical values in determining whether or not to inject into lunar orbit. Therefore, fuel remaining must be measured each time a mid-course guidance correction is made, and curves must be plotted to extrapolate the rate-of-boiloff data.

As was mentioned above, the purpose of monitoring these displays is to determine system operational status. Ultimately, the information gained from this process is used in a particular type of decision-making behavior. Given a particular situation, the Pilot-Commander must choose between several possible alternatives, these alternatives being:

(1) Abort the mission--return to earth as quickly as possible.

(2) Change mission parameters--instead of attempting to complete a lunar orbit mission, attempt to complete:

- (a) Earth-orbit mission
- (b) Cislunar mission
- (c) Circumlunar mission

(3) Attempt to complete a lunar-orbit mission

This decision-making process can be divided into several steps:

(1) Display readings must be interpreted in terms of normal system operation or equipment malfunctions.

(2) The particular system malfunction, if one exists, must be detected and isolated.

(3) Determined whether maintenance can be performed

(4) If maintenance can be performed, then it should be attempted.

(5) If maintenance is not possible, then the Pilot-Commander must determine, on the basis of reliability estimates, their chances for a successful mission completion, without the use of the malfunctioned equipment, either operationally, or as a back-up.

(6) The position of the vehicle in space must be considered, in order to determine whether it is possible to abort.

For any one particular equipment malfunction, it is not too difficult to make a decision to abort, to change mission parameters, or to continue the mission. An in-flight systems check will be presented later which will allow for a decision to be made whether to abort prior to injection phases. However, when there are a combination of reduced system performances or equipment malfunctions, the decision is clearly a difficult one. Since there obviously exist conditions where a great deal of judgment is involved, as to estimating successful mission completion, the possibility of programming a computer to make this decision is out of the question. Also, a great deal would depend on what estimated probabilities of successful mission completion the crew would be willing to accept and still continue.

In the operation of the guidance system, the most critical system during cislunar flight, man plays an important and necessary role. The Navigator-Pilot, at various intervals during a navigation fix, will have to compare angular information obtained from on-board automatic and on-board manual tracking systems. He will use certain accuracy criteria charts to accomplish this information processing task. The results of this comparison will be used to compare the operational status of his trackers and inertial platforms, and determine if either set of equipment is not operating properly.

After the raw data from the two on-board navigational systems (i.e., the manual system and the automatic system) and the two ground tracking systems have been converted by the computers into four sets of data concerning deviations from nominal trajectories, (ΔX, ΔY, ΔZ, ΔT, $\Delta \dot{X}$, $\Delta \dot{Y}$, $\Delta \dot{Z}$) the Navigator-Pilot must compare these sets of data for general agreement and discover a "best" weighting factor for each set of data in order to obtain the most accurate trajectory determination. The comparison will also have accuracy limits associated with the various sets of data, however, the determination of a "best" weighting factor will be essentially a trial-and-error process, although inherent accuracies associated with each system can be utilized to aid guesses as to "best" weighting factors. Other factors which might be considered in the determination of these calculations are intermittent performance, insufficient samples, internal cabin conditions, crew performance, etc.

In order for the digital computer to determine the mid-course guidance correction parameters, (duration of thrust and vehicle attitude) the Navigator-Pilot will select several aim points, steering correction times, and nominal trajectories to be considered. In selecting these sets of data, on which the computer computations will be based, the Navigator-Pilot will use information, in the form of graphs, concerning ranges of maximal effectiveness in terms of fuel consumption. However, he must pick discrete points within these ranges, points which he feels will minimize fuel consumption.

After the computer has calculated the sets of correction parameters, based on the data supplied by the navigator, he will pick the most optimal correction in terms of fuel consumption. Now the navigator must, using this optimal correction, decide whether a correction will actually be performed. This decision will be in part based on the comparison of the required correction velocity to the uncertainty of readings from the navigation system. However, the ultimate decision, made by the Pilot-Commander, must also consider systems status. This information will be conveyed to the Pilot-Commander by the Engineer-Scientist.

In all of the above described activities, there are certain predetermined criteria, however gross, that man uses to aid him in making decision. However, man's most important contribution to Apollo, lies in the areas where there are no preplanned standards. In fact, there do not exist any predetermined ways of reacting to given situations in space flight situations.

For example, suppose that immediately after igniting the main engine for an injection into lunar orbit, the crew member monitoring main engine performance finds that thrust levels are much less than expected, and that the main engine will expend all remaining fuel before giving the vehicle the velocity decrement to inject it into a lunar orbit. Since the Navigator-Pilot will have a continuous indication of inertial velocity and inertial attitude, it may be possible to shut the engine down, reverse the vehicle attitude 180°, and fire the main engine to counteract the original velocity impulse. This would serve the purpose of putting the vehicle into a circumlunar orbit and the mission would not be a complete failure.

The malfunction described above is unlikely; however, if we consider that there is a finite probability of its occurrence; then we must conclude that the inclusion of man in the Apollo vehicle, has greatly increased the probability of a successful mission completion.

The possibility of many situations, similar to the one described above, can be predicted, along with the set of conditions which will maximize the results. Such situations will place a great deal of emphasis upon ingenuity, creativity and judgment, and since the Apollo crew members are the only subsystems possessing these characteristics, their value in the system is obvious. Table 1-3 presents number of information channels monitored per phase and Table 1-4 presents the number of decisions made per phase. These tables emphasize the involvement and decision control the crew has over the Apollo system.

TABLE 1-3

Number of Information Channels Monitored Per Phase

Mission phase	No. of channels Monitored
Launch	39
Coast	8 *
Injection into Trans-Lunar orbit	47
Trans-Lunar orbit	203 *
Injection into Lunar orbit	38
Lunar orbit	109 *
Injection into Trans-Earth orbit	38
Trans-Earth orbit	244 *
Re-Entry	24
Systems Check (Done during coast and prior to and subsequent to Injection into both Lunar orbit and trans-earth orbit	122

* Not including systems checks

TABLE 1-4

Decision-Making Behavior Per Phase

Mission phase	Number of decisions made
Launch	10
Coast	3 *
Injection into trans-lunar orbit	7
Trans-lunar orbit	48 *
Injection into lunar orbit	7
Lunar orbit	28 *
Injection into trans-earth orbit	7
Trans-earth orbit	51 *
Re-entry	6
In-flight systems check (done during coast and prior to and subsequent to injection into and ejection out of lunar orbit)	63

* Not including system check

Continuous psychomotor activity. During re-entry and at various times during trans-lunar, lunar and trans-earth phases of the lunar orbit mission, the Pilot-Commander will re-orient vehicle attitude.

During the majority of time in deep space, the vehicle will be oriented with the nose pointing toward the sun, for the purpose of keeping propellant boil-off to a minimum. However, there are times during the mission when the attitude must be changed from a sun-oriented position. These times are:

(1) Prior to each set of star, moon and earth measurements

(2) Prior to each photographic scientific reconnaissance sequence

(3) Prior to each midcourse guidance correction

(4) Prior to injection into and ejection out of lunar orbit

(5) Prior to re-entry.

As an initial estimate, the pilot may have to change vehicle attitude perhaps 65 to 70 times during a lunar mission, while in deep space.

During re-entry, the Pilot-Commander will have continuous control of the vehicle flight-path. However, this entire process can be divided into a number of phases. After releasing the mission module and before entering the atmospheric boundary of aerodynamic control, vehicle attitude is controlled by command module attitude rockets. When the atmosphere becomes dense enough to allow aerodynamic control of the vehicle, this control will be accomplished by three flaps, extending from the rear of the command module. At about 80,000 ft from the surface of the earth, the drogue chute is deployed and temporarily, the pilot's control of the vehicle ends. At 15,000 ft, the main chute is extended and the pilot now controls vehicle flight path by manipulating a flap in the chute.

All above mentioned control (midcourse attitude, re-entry) except chute maneuvering control is accomplished by using a two-axis electric stick and electric yaw pedals. There are only two axes of maneuverability in the chute control, so that only one axis of the stick and the yaw pedals would be used during this sequence.

Discrete psychomotor activity. Upon examination of the list of discrete psychomotor functions, the crew accomplish during a lunar orbit mission, it is seen that they obviously play a large role in the system. Especially so, when it is considered that they repeat some of these functions many times over.

If we consider that these functions would be design parameters or specifications, the amount of mechanized equipment saved by giving these functions to the crew is quite large.

To automate all switching functions listed on the following pages, it would be necessary to include various sensors and associated switching circuitry, in order to determine what and when to switch. For example, signal strength for both VHF and deep space net communications systems must be sensed and compared, to determine when to switch systems subsequent to injection into trans-lunar orbit. It is necessary to sense time in order to determine when to initiate a mid-course guidance fix.

If mission parameters change while in flight, this information must be transmitted to the switching mechanisms. For example, if, after injection into trans-lunar orbit is completed, it is decided to only attempt a cislunar orbit mission instead of a lunar orbit mission, obviously, some of the lunar surveillance equipment would not be activated.

An equipment malfunction or an absolute drop in equipment output must be sensed before the system can be switched to a redundant one. It will also be necessary to compare outputs from two or more systems to determine which system outputs should be utilized.

It is necessary to sense time in order to determine when to initiate a mid-course guidance fix sequence. Also, at various times during the sequence, the completion of previous expected operations must be sensed before other operations can be initiated.

Aside from the sensing and switching mechanisms that must be included in an automated system, there must be a large amount of additional computer circuitry and memory space and computer input-output devices.

Essentially, allowing the crew to accomplish these switching functions has several advantages:

(1) It decreases the weight of additional sensors, switching mechanisms, computer circuitry and computer input-output devices.

(2) As these elements would obviously be attached in series, the reliability of the system is increased by the inclusion of man.

(3) The flexibility of the system is increased, as the crew can adjust their outputs to variable situations more rapidly and with less complexity than can an automated system.

Table 1-5 summarizes the number of discrete psychomotor tasks performed by the Apollo crew during a lunar orbit mission. In performing these tasks, the crew saves the equipment necessary to perform a total of 998 switching or adjusting functions.

TABLE 1-5

Number of Discrete Psychomotor Tasks Per Phase

Mission phase	Number of tasks
Launch	5
Coast	5 *
Injection into trans-lunar orbit	0
Trans-lunar orbit	271 *
Injection into lunar orbit	0
Lunar orbit	178 *
Injection into trans-earth orbit	0
Trans-earth orbit	330 *
Re-entry	4
Systems check (Done during coast and prior to and subsequent to injection into both lunar orbit and trans-earth orbit)	207

* Not including systems checks

The following is a list of discrete psychomotor tasks for Apollo subsystems:

Communications system

(1) Switch from VHF to deep space net after injection into trans-lunar orbit.

(2) Turn off C-band transponding beacon after injection into trans-lunar orbit.

(3) Switch from deep space net to K_e band just prior to re-entry

(4) Switch from K_e band to VHF after touchdown

(5) Turn on deep space net antenna extension controls

(6) Turn on C-band transponding beacon just prior to re-entry

(7) Turn off deep space net at those times during lunar orbit phase when vehicle communications are blocked by the moon.

(8) Turn on deep space net at those times during lunar orbit phase when vehicle communications are not blocked by the moon.

(9) Adjust volume when earth signals grow weak.

Environmental control system

(1) Switch from LiOH filter system to molecular sieve filtering system after injection into trans-lunar orbit.

(2) Switch from command module O_2 and N_2 supplies to mission module O_2 and N_2 supplies when the former is exhausted (probably some time during lunar orbit).

(3) Switch on mission module ventilating system subsequent to injection into trans-lunar orbit.

(4) Turn on radiator coolant loop during coast phase.

(5) Switch to back-up radiator coolant loop in case of failure of primary system.

(6) Switch atmosphere (O_2 and N_2) supply from pressure suit to mission module subsequent to injection into trans-lunar orbit.

(7) Switch atmosphere (O_2 and N_2) supply from mission module to pressure suit prior to re-entry.

(8) Reduce pressure in mission module, just prior to releasing it, to check on quality of seal between the command and mission modules.

Propulsion system

(1) Switch off main or vernier propulsion systems in deep space in case of abnormal firing.

(2) Switch from non-operational attitude rocket to back-up attitude rocket in case of failure.

(3) Switch two-axis stick and rudder pedals from control of attitude rockets to control of flaps, just prior to re-entry.

Control system (two-axis stick and yaw pedals)

(1) Switch stick and yaw pedals from control of attitude rockets to control of flaps (just prior to re-entry).

(2) Switch one axis of stick and yaw pedals from control of flaps to control of main chute (just prior to deployment of main chute).

Hot gas system

(1) Switch on hot gas system immediately prior to re-entry

(2) Switch to back-up hot gas system in the event of failure of the operational system.

Electrical system

(1) Switch non-essential buses off line where there is equipment failure and maintenance is to be attempted—switch bus on line when maintenance is completed.

(2) Switch fuel cells in case of drop in output

(3) Switch from fuel cell bus to recovery bus just prior to dropping mission module or if fuel cells should malfunction.

(4) Switch control operating battery charging system, anytime the battery is used during deep space.

(5) Turn-off battery and turn on Recovery Power Unit subsequent to touchdown.

Guidance system

(1) Switch on automatic guidance routine when a fix is desired

(2) Enter Telesextant readings in computer memory after each star, earth and moon reading

(3) Select computer programs to compute and/or display various parameters.

(4) Enter guidance data into panel to be transmitted to earth

(5) Select charts, graphs, etc., from the slide projector

(6) Enter propulsion system parameters for midcourse guidance corrections and injections into correction control panel.

Miscellaneous psychomotor activities

(1) Back-up 1st stage release during launch

(2) Back-up escape tower release during launch

(3) Back-up 2nd stage release during launch

(4) Back-up 3rd stage cutoff during launch

(5) Back-up 3rd stage separation after injection into trans-lunar orbit.

(6) Open passage between mission module and command module after injection into trans-lunar orbit.

(7) Close and seal passage between mission module and command module prior to releasing mission module.

(8) Back-up mission module release

(9) Switch off attitude rockets subsequent to entering atmosphere

(10) Back-up drogue chute release during re-entry

(11) Back-up main chute release during landing sequence

(12) Back-up for retro-rocket firing during landing sequence

(13) Emergency booster cut-off control for abort during launch

(14) Abort control (during launch).

Troubleshooting and maintenance. The most important aspect of maintenance which can be delineated from the sequential activities analysis are the crew functions which determine mission status. This has been determined for coast periods prior to injection phases. It is termed an in-flight systems check.

The sequence of events within the in-flight systems check includes all processes which will be necessary to check the operation of all systems. As seen in the flow diagram, this sequence is initiated during coast, prior to and following injection into and ejection from lunar orbit.

The reason for the systems check is to supply the crew with a more comprehensive evaluation of system operation than can be gained from monitoring system status alone. The systems check includes switching from operation to back-up equipment and measuring performance, feeding artificial signals to various systems and measuring outputs, and examining present system levels and projecting them ahead in time to predict future conditions. The results of the systems check will give the crew a more adequate picture from which to make a decision to abort, to continue the lunar orbit mission or to change mission parameters (i.e., from lunar orbit mission to circumlunar, cislunar of earth orbit mission).

A breakdown of the sequence of events in the in-flight systems check by subsystem is as follows:

<u>In-flight communications systems check. There are five communications and telemetry systems aboard. They are:</u>

(1) C-band beacon-launch and recovery tracking

(2) S-band beacon-launch and deep space tracking

(3) VHF band-launch and recovery communications

(4) Deep space net-Communications from injection to re-entry

(5) K_E band-communications during re-entry

Absolute or relative power output is not important as an abort determiner. However, an uncontrollable drop or fluctuations in output power, modulation level, supply voltages, and/or receiver gain control is an indication of unstable system performance, however, there can be no prediction made of time of ultimate system failure from any of these measures. Thus, rate of fluctuation or rate of drop cannot be quantified to measure system performance.

During coast, a systems check for the communications system would consist of the following sequence:

(1) Check output power, modulation level, supply voltages and receiver gain control for normal operating and redundant back-up systems of C-band, S-band, VHF, deep space net and K_E*. Here, the Engineer-Scientist would be looking for drops or fluctuations in these measures.

(2) Send test message to ground over VHF, deep space net, and K_E* and receive same message, for both normal operating and redundant back-up systems. The criteria would be audibility of message reception, both by ground and by vehicle.

Tentatively, abort decisions would be made on the following basis:

	Deep Space Net	C-band beacon	S-band beacon	VHF
One system normal, one system questionable	No Abort	No Abort	No Abort	No Abort
Both systems questionable	Crew Option	Crew Option	No Abort	Crew Option

*There is only one K_E system aboard, however, questionable operation of this system would not lead to an abort decision. Since the antennas cannot be erected until after injection into trans-lunar orbit. Due to one space g forces during injection, the antennas, antenna erection system and antenna controls cannot be checked during coast.

In deep space, the C-band beacon and the VHF system cannot be checked. However, the antennas and antenna controls can be checked by rotating the antennas, using both manual and automatic modes, and this will be done.

The above discussion is obviously dependent on the amount of maintenance that it is possible to perform on the system and any abort decision would also just as obviously depend on the amount of maintenance that can be attempted.

In-flight space environment systems check. The Engineer-Scientist must check values for two measures; radiation dose and projected meteorite occurence level. The first projected step is to ascertain the present accumulated radiation dose. Then the vehicle's trajectory must be ascertained. There will be charts and tables onboard that will show schedules of projected radiation dose versus time for several different trajectories. From the present level at a given time on a given trajectory, the total expected dose for a 14-day lunar orbit mission can be obtained. If this expected dose has a probability of accumulating to a level of 100 REM above that which has previously been decided upon, the 14-day lunar mission would be aborted, and other temporarily shorter missions (e.g., translunar mission, cislunar mission) would be examined in terms of probable expected dose accumulation. This entire sequence should take somewhere between two to five minutes.

The same process is followed in determining the probability that a present meteorite occurrence level will lead to an accumulated meteorite occurrence level above a predetermined safe value for a 14-day lunar orbit mission. The determination of this level, unlike radiation dose prediction, is independent of vehicle trajectory. This calculation would also take from two to five minutes.

In-flight environmental control systems check. The process of checking the environmental control system during coast would proceed as follows:

(1) Check displays in command module:

(a) O_2 partial pressure-detection of malfunction in O_2 supply.

(b) CO_2 partial pressure-detection of LiOH filter malfunction.

(c) Total cabin pressure-detection of malfunction in N_2 supply.

(d) Cabin temperature-detection of fan malfunction or cooling system failure.

(e) Cooling system pressure-detection of leak in cooling system.

(f) Pressure flow rate-detection of malfunction in N_2 supply.

(g) Relative humidity-detection of malfunction in H_2O separator.

(h) Electrical equipment temperature-detection of malfunction in fans.

A check of these displays would indicate command module system operation. However, the mission module environment is not as easily checked. The sequence to check this would include the following tests:

(1) Monitor mission module total pressure for leak detection.

(2) Open mission module ventilating valves (located in command module); turn off command module fans and turn on mission module fans. By observing an air flow, the condition of the ventilating duct and the operation of the mission module fans can be checked.

(3) While still using the mission module ventilating system (ducts and fans) switch from LiOH filter to molecular sieve filter, but continue to use the command module O_2 and N_2 supplies. By observing the buildup of CO_2, if any, the condition of the molecular sieve filter can be deduced. This procedure should take approximately one-half hour.

(4) Turn on the radiator coolant loop and observe the pressure and whether there is a temperature increment or decrement (depending on whether the radiators are still hot from launch). If the pressure is normal (50–60 psi) and there is a temperature change within one or two minutes, the cooling system is operating normally.

A total abort would be decided upon, due to:

(a) Leak in command or mission modules

(b) Loss of one cooling system

(c) Loss of molecular sieve

The mission parameters would be changed (i.e., from lunar orbit to circumlunar orbit, cislunar orbit or earth orbit) in case of stoppage in O_2 or N_2 supply in the command module. There is no way of checking the O_2 and N_2 supplies during coast, due to the seal between the two modules. However, since 50% of the total O_2 and N_2 supplies is in the mission module, this would have to be checked immediately after opening the door (after injection into translunar orbit). This will be done both after injection and at the other times in deep space, when the systems check takes place, by activating the flow in the supply lines and observing pressure flow rates, cabin total pressure and O_2 partial pressure.

In-flight propulsion systems check. The only way to predict if the various on-board propulsion units will function properly on demand is to activate them and note the resulting effects. However, all on-board propulsion units are contained in the fairing between the S-IV Saturn boost vehicle and the propulsion equipment module and there exists no outlets for trapped gases to escape. Therefore, during coast, when the S-IV and the space craft have not yet separated, there is no way of testing the actual operation of the units. However, various portions of the system can be checked. The procedure is as follows:

(1) Arm vernier and attitude propulsion systems:

 (a) Turn on switch which controls evacuation of the lines in the attitude and vernier systems.

 (b) Turn on switch to pressurize propellant tanks.

(2) Monitor chamber pressures-This indicator should read zero, showing that there are no leaks in the system.

(3) Monitor other propulsion system displays:

 (a) Pressure tank pressure: 4500 psi (normal)
 4760 psi (max.)

(b) Pressure tank temperature: 70° F (normal)
100° F (max.)

(c) Propellant tank pressure: 60 psi (normal)
50 psi (min.)
120 psi (max.)

(d) Propellant quantity in main tanks:

O_2 boiloff rate = 0.26 lbs. per hour (starting from lift-off).

N_2 boiloff rate = 0.43 lbs. per hour (starting from lift-off).

(e) Thrust chamber pressure: zero

(f) Propellant inlet pressure: zero

(g) Main tank pressure: 15 psi (normal)
16 psi (max.)

The values stated above are design limits, not including the safety factor, so that if any of these pressures reach the above-stated limits, the mission would be aborted, and the vehicle would re-enter the atmosphere and land. However, after the propulsion system has been armed, the temperature of the fuel in the lines will rise slightly, possibly causing a slight rise in pressures throughout the system. This should be considered normal.

If a vernier correction is not attempted immediately after injection, the vernier rockets should be tested by firing them, rotating the vehicle 180°, and applying a counter-thrust. This would also be done while in deep space.

All values of measurements, given above, except one, will be considered to be system failures and therefore warrant an abort trajectory. The main engine fuel boil-off rates exceeding normal values would not warrant an abort, but only a change in mission parameters to circumlunar or cislunar orbit.

In-flight re-entry systems check. During coast, the parts of the re-entry system to be checked are: section of the computers controlling re-entry, re-entry autopilots, and the re-entry CRT displays.

First, a prearranged and preprogrammed test problem will be carried out by the computers. The output will be observed on the CRT re-entry displays. Thus, the computer re-entry circuits and the operation of the CRT displays can be checked.

Next, the computer would be activated to feed a step or ramp input to the autopilot system. The output of the autopilots would be observed as a qualitative indication (e.g. red light). Essentially, it is a go-no-go situation.

An abort may be decided upon on the following parameters:

(1) Loss of one computer

(2) Loss of both CRT re-entry displays

(3) Loss of re-entry autopilot system

The concept of the re-entry engineers is to design the autopilots and computers for a maximum amount of in-flight maintenance, so that, for example, if both re-entry autopilots malfunction, the Engineer-Scientist may decide to inject and attempt maintenance subsequent to injection. Therefore, all abort criteria should be considered as crew decisions.

In-flight hot gas systems check. The re-entry control flaps cannot be checked, as they are enclosed by a metal fairing. However, some parts of the system can be activated and checked. The fuel tank pressure should read 2800 psi. The systems (one normal and one redundant) should be turned on to check the gas generator output. The readings for pressures and temperatures should be, respectively, 1200 psi (normal) $\pm 5\%$ and 1400°F (max.). Here the crew is more concerned with fluctuations and/or uncontrollable drops.

An abort would be decided upon if there is a loss of one hot gas system, although this is essentially a crew decision and depends on their confidence in the remaining system.

The whole process of checking out this system should take in the order of one to two minutes to complete.

Coast electrical systems check. There are many aspects of the electrical power system that can be checked during coast. The sequence would proceed as follows:

(1) Battery check:

(a) Switch the fuel cells of the line

(b) Switch the battery on the line

(c) Check output voltage (should be 28 volts)

(d) Switch fuel cells back on line

(e) Check to see that the battery is being recharged.

(2) Fuel cell and voltage regulator check:

(a) Turn off one fuel cell at a time

(b) Observe to see if the other two pick up the load and whether they do so evenly.

(c) Observe temperature. (normal -450°F)
(max. - 500°F)
(min. - 375°F)

(d) Observe ΔP (2 psi < normal operating ΔP < 6 psi).

(e) Observe bus voltage. (normal - 28 volts)
(max. - 28.5 volts)
(min. - 26 volts)

(3) Valve, tubing and manifold check:

(a) Switch from auxiliary tanks to main tanks.

(b) Observe ΔP (2 psi < ΔP < 6 psi)

(c) Switch back to auxiliary tanks.

(d) Switch manifolds from right side to left side.

(e) Observe ΔP (2 psi < ΔP < 6 psi)

(f) During the whole process, every time a switch occurs, the Hi-Flow warning light should come on. This would also be an indication of the status of the flow meters.

(4) H_2O separator and temperature regulator check:

(a) Turn off the operational H_2O separator

(b) Observe temperature - it should remain steady at 450°F for a short time and then rise.

(c) When the temperature rises to 500°F (about 20 seconds after it starts to climb) switch to the alternate H_2O separator.

(d) The temperature should drop to 450°F.

(5) Bus flag and load meter check:

(a) Switch off non-essential bus switches

(b) Observe flag indicators and change in load meter readings.

TABLE 1-6

COAST SYSTEMS CHECK FOR GUIDANCE SYSTEM

Sequence	Subsystems	Procedure	Accuracy	Abort Decision	Time for Check
1	(1) Astroplatform (Window and Cover)	(1) Open cover, change position	(1) Normal response	(1) Abnormal	1 min 2 crew members
		(2) Check window flatness	(2) 10 sec arc	(2) Abnormal	
	(2) Telesextant (Window and Cover)	(1) Same as Astroplatform	(1) Same as Astroplatform	(1) Abnormal	
	(3) Radar Altimeter	(1) Near earth and near moon compare readings with navigation system readings	(1) 2000 feet	(1) No abort if malfunction	
2	(1) Astroplatform	(1) Electronic check	(1) Signal occurrence	(1) Abnormal	

TABLE 1-6 (Cont)

COAST SYSTEMS CHECK FOR GUIDANCE SYSTEM

Sequence	Subsystems	Procedure	Accuracy	Abort Decision	Time for Check
		(2) Torque gyros to check platform	(2) Angular motion	(2) Abnormal	5-8 min 2 crew members
		(3) Astro-tracker check and realign platform if neces-sary	(3) Signal occurrence	(3) Abnormal	
		(4) Acceler-ometers for null check	(4) 10^{-4} g	(4) Abnormal	
	(2) Tele-sextant	(1) Check servos	(1) Response	(1) No abort if malfunction	5-8 min 2 men
		(2) Check automatic readout and com-pare to manual readout	(2) 30 sec com-parison	(2) Abnormal	

COAST SYSTEMS CHECK FOR GUIDANCE SYSTEM

Sequence	Subsystems	Procedure	Accuracy	Abort Decision	Time for Check
3	(1) Miniature platform	(1) Electronic check	(1) Signal occur- rence	(1) Abnormal	1 man 7.5 min
		(2) Torque gyros and platform operation check	(2) Angular motion	(2) Abnormal	
		(3) Realign platform	(3) Normal response	(3) Abnormal	
		(4) Acceler- ometer check for null	(4) 10^{-4} g	(4) Abnormal	
4	(1) Com- puter 1	(1) Check (3 check problem run)	(1) Normal response	(1) Abnormal	2 men 3 min
	(2) Com- puter 1	(1) Same as above	(1) Same as above	(1) Abnormal	

Depending on the reliability of the system and the confidence of the crew in the operation of the system, the following malfunctions may cause the crew either to abort or to alter the mission profile.

(1) One H_2O separator malfunctioning.

(2) One manifold malfunctioning.

(3) One fuel cell (or associated valving) malfunctioning.

The crew would probably not abort in case of a complete battery failure, as the battery is used for re-entry, and they must re-enter under any type mission or abort.

The entire check, as described above, would take in the vicinity of 10-12 minutes.

In-flight guidance systems check. This table is presented in the sequence of the subsystem checks, it also defines the crew requirements and time necessary for each check. The total time necessary to complete the systems check is approximately 28 minutes.

e. Rendezvous

The Apollo system may also have a rendezvous with another manned space station or an unmanned communications, reconnaissance satellite or refueling system. The concept is that the vehicle will be ground launched, injected into a planned orbit, complete a mechanical connection with the target vehicle (in order to carry out the rendezvous function) and then return by a controlled landing to a designated landing area.

The purposes of rendezvous are multiple. Regarding unmanned reconnaissance and communications satellites, it is quite apparent that repairs and maintenance will become necessary. Manned space platforms and laboratories are also likely to require maintenance and repair. In addition, manned satellite rendezvous is required for logistic purposes, crew rotation, and refueling. The proposed Apollo space vehicle will adequately fulfill any of the mentioned rendezvous missions. We have therefore attempted to analyze the crew functions relative to the rendezvous mission.

Mission requirements. The major mission phases when utilizing the Apollo system as a rendezvous vehicle may be generally considered to be the following: (1) prelaunch, (2) boost, (3) rendezvous, (4) de-orbit, (5) re-entry, (6) re-entry completion and (7) landing. The phases pertaining to boost (2), rendezvous (3) and de-orbit (4) are the only phases differing from other regular Apollo vehicle missions. A rendezvous sequential activity analysis is presented in this section with an interpretation.

Prelaunch - - This initial phase concerns all events which occur in order to check out and prepare the vehicle for launch. Vehicle crew and ground command, through a sequence of preparatory checks, determine if all subsystems, (propulsion, guidance, control, communications, telemetry, power, environmental, etc.) are ready or functioning properly as design characteristics of the Apollo vehicle require for actual launch.

Boost - - This phase includes all events between the time the actual firing signal occurs and propulsion termination of the injection rocket. It must be emphasized that the conditions existing at the time of burnout, determine and control the vehicle's orbit, which is a result of the launching and powered flight sequence (this may be considered as achieving a planned orbit).

Rendezvous - - The vehicle crew is concerned with attaining rendezvous with the target satellite immediately after achieving orbit. The rendezvous mission is achieved with the transportation of personnel and/or material to the satellite vehicle through an attached air lock between both vehicles. This is discussed below.

Guidance and control are critical in attaining rendezvous. Essentially the crew must inject into the plane and orbit of the target vehicles. This is necessary if the rendezvous vehicle is to <u>remain</u> in the proximity of the target satellite within an arbitrary range; with only minor errors in the orbital plane, altitude and other parameters.

The approach to and detection of the target satellite will be accomplished by the crew members utilizing the radar altimeter, with displays indicating the distance from the target, and the rate of approach to the target. After lock-on has been made and the radar is tracking the target satellite, two displays, giving azimuth and elevation track angle readouts, are presented in vehicle coordinates so that an area of search for visual detection is defined.

Visual detection of the target satellite is performed by a space scope display which presents an optically projected view (or an electronically projected view) with a visual field of 80-90 degrees. The vehicle's external environment during flight, and optical determination of range and look angles to the target satellite, may be accomplished and determined by this display and its associated controls. The display screen will contain a vertical and horizontal intersecting crosshair in the center of the display area, which will serve as references to aid in centering the target vehicle on the display screen. The target display-image horizontal and vertical look-angles can be read directly from the display.

The Apollo crew members, while concerned with the detection and approach of the target satellite, will also have other critical areas of concern during a rendezvous mission, e.g., guidance and control. In order to attain a planar orbit similar to that of the target satellite, velocity, flight path angle, attitude, pitch, roll and yaw angles and rates need to be determined, corrected and/or maintained. Latitude, longitude, inclination, vernier jet control and other aspects of guidance and control information can be transmitted to crew members, and controlling functions can be completed by them without additional displays.

After guidance and control functions have brought the vehicle into a planar orbit similar to that of the target vehicle with relative speeds and a maximum distance of two hundred feet, actual contact may be completed in one of two ways. A small rocket with an infrared seeker system with a cable attached is fired from one vehicle to an infrared target on the other vehicle. After cable connection, a reel brings the vehicles together and mechanical connection between the air lock and hatch is made.

The second method consists of a cable suspended on retracting arms of the satellite which engages hooks on the other vehicle. The vehicles are stabilized relative to each other, and the cable is then reeled to bring the vehicles together so that the air lock and hatch are connected.

De-orbit - - This phase is initiated upon rendezvous completion. The conditions of velocity, orientation of the velocity vector and altitude at the cutoff of the retro-rocket thrust determine the angle of re-entry into the earth's atmosphere.

Re-entry, completion and landing - - After leaving circular orbit the vehicle is injected into a determined re-entry profile and into the designated re-entry corridor, then terminates with a controlled landing at a designated landing area.

2. <u>Apollo Task Analysis</u>

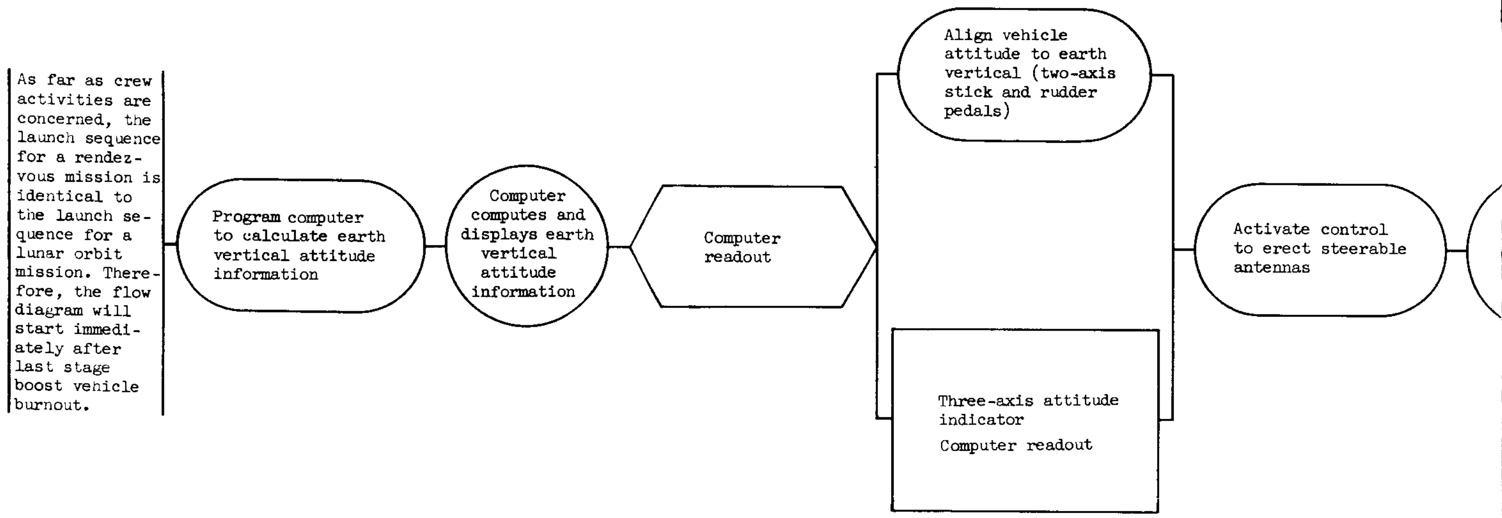
The Apollo task analysis is another method of describing man's functions during a lunar orbit mission. Basically, it consists of a sequential list of the crew's tasks and sub-tasks, along with those display and control parameters which would ultimately enable the crew to accomplish their functions.

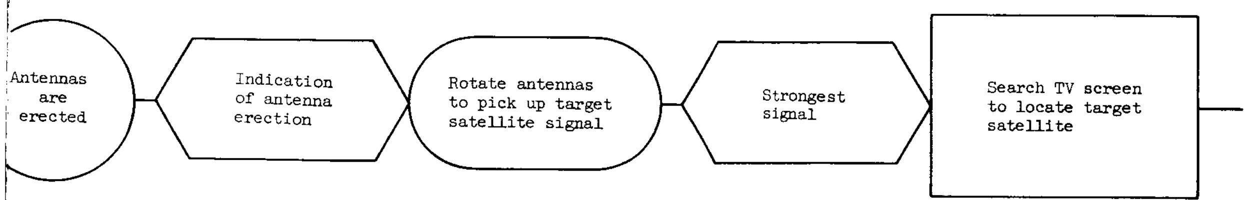
To understand the reason for a task analysis it is essential to first state that the task analysis should not be viewed as the final goal of the human factors effort. The task analysis is of prime value when used as a basis for further human factors efforts. The task analysis provides another systematic method for studying the entire mission in both overall viewpoint and specific detail.

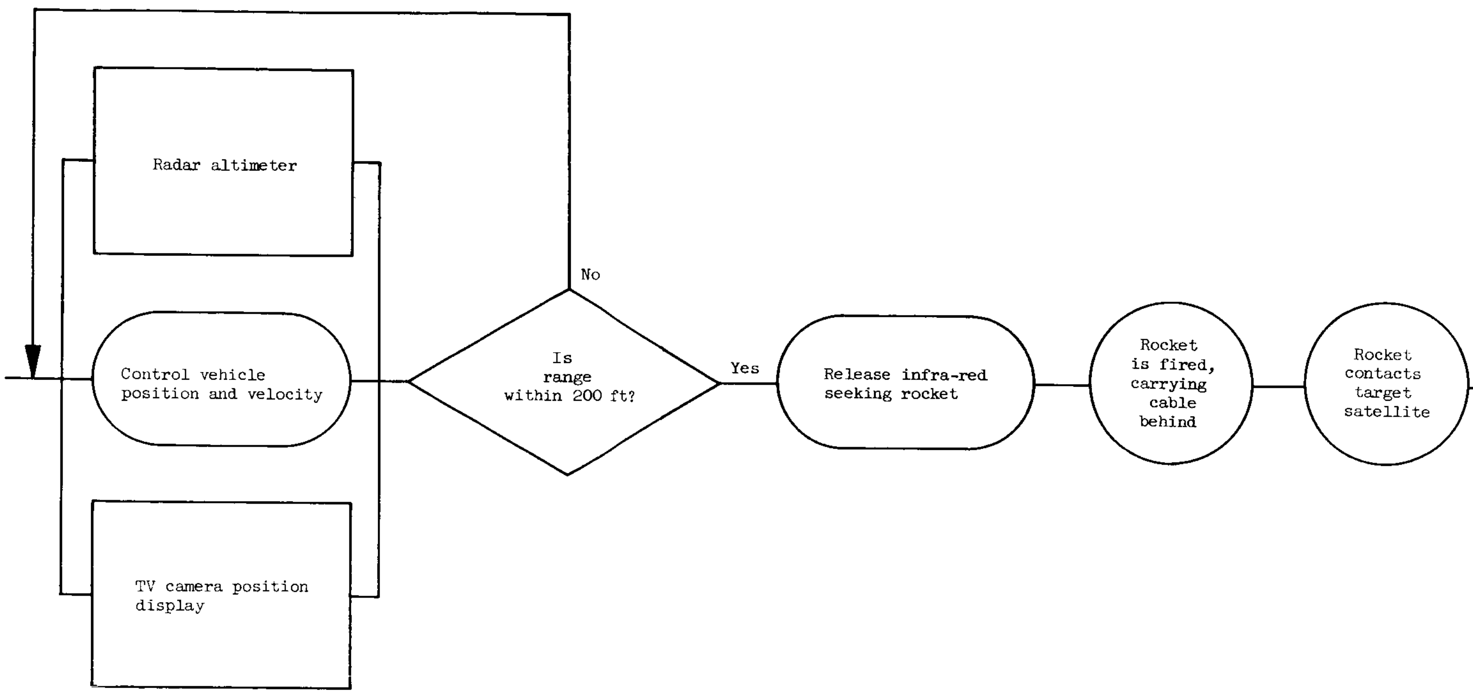
a. Description

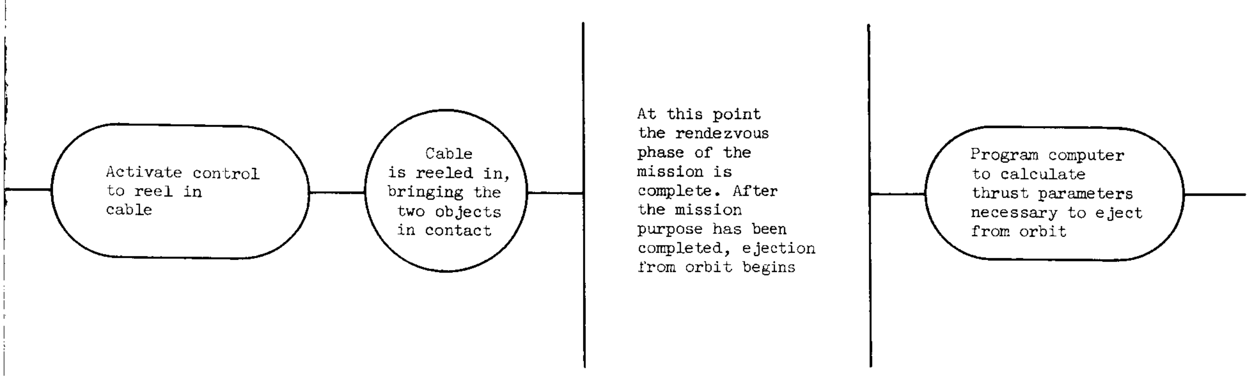
The lunar orbit mission was split into different phases (launch, coast, injection into trans-lunar orbit, trans-lunar orbit, injection into lunar orbit,

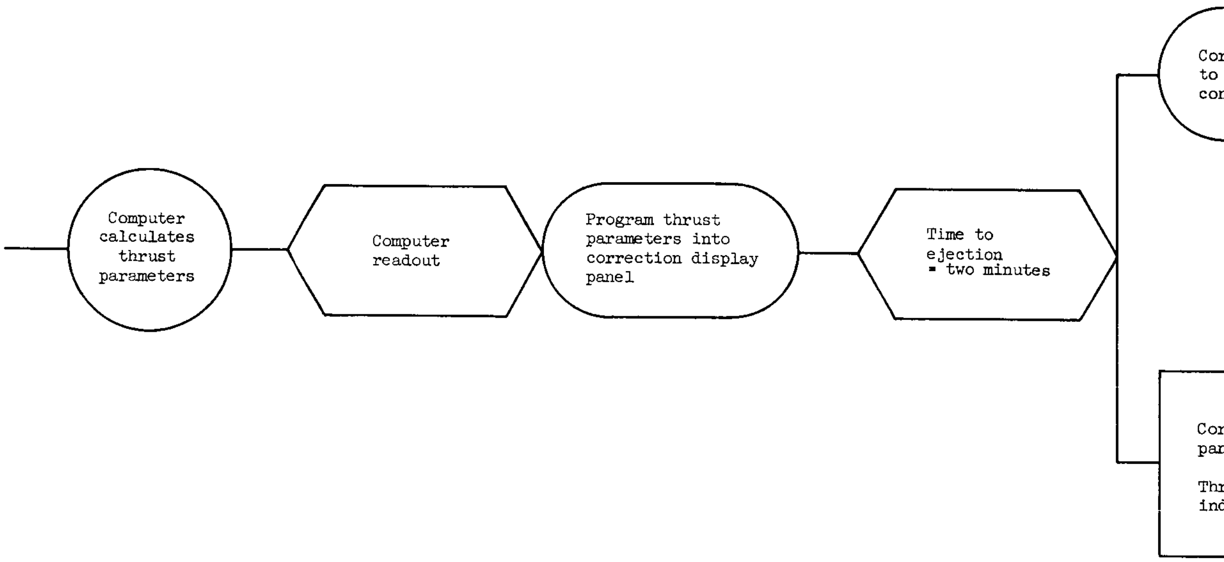
[redacted]


As far as crew activities are concerned, the launch sequence for a rendez-vous mission is identical to the launch se-quence for a lunar orbit mission. There-fore, the flow diagram will start immedi-ately after last stage boost vehicle burnout.
Program computer to calculate earth vertical attitude information
Computer computes and displays earth vertical attitude information
Computer readout
Align vehicle attitude to earth vertical (two-axis stick and rudder pedals)
Three-axis attitude indicator
Computer readout
Activate control to erect steerable antennas

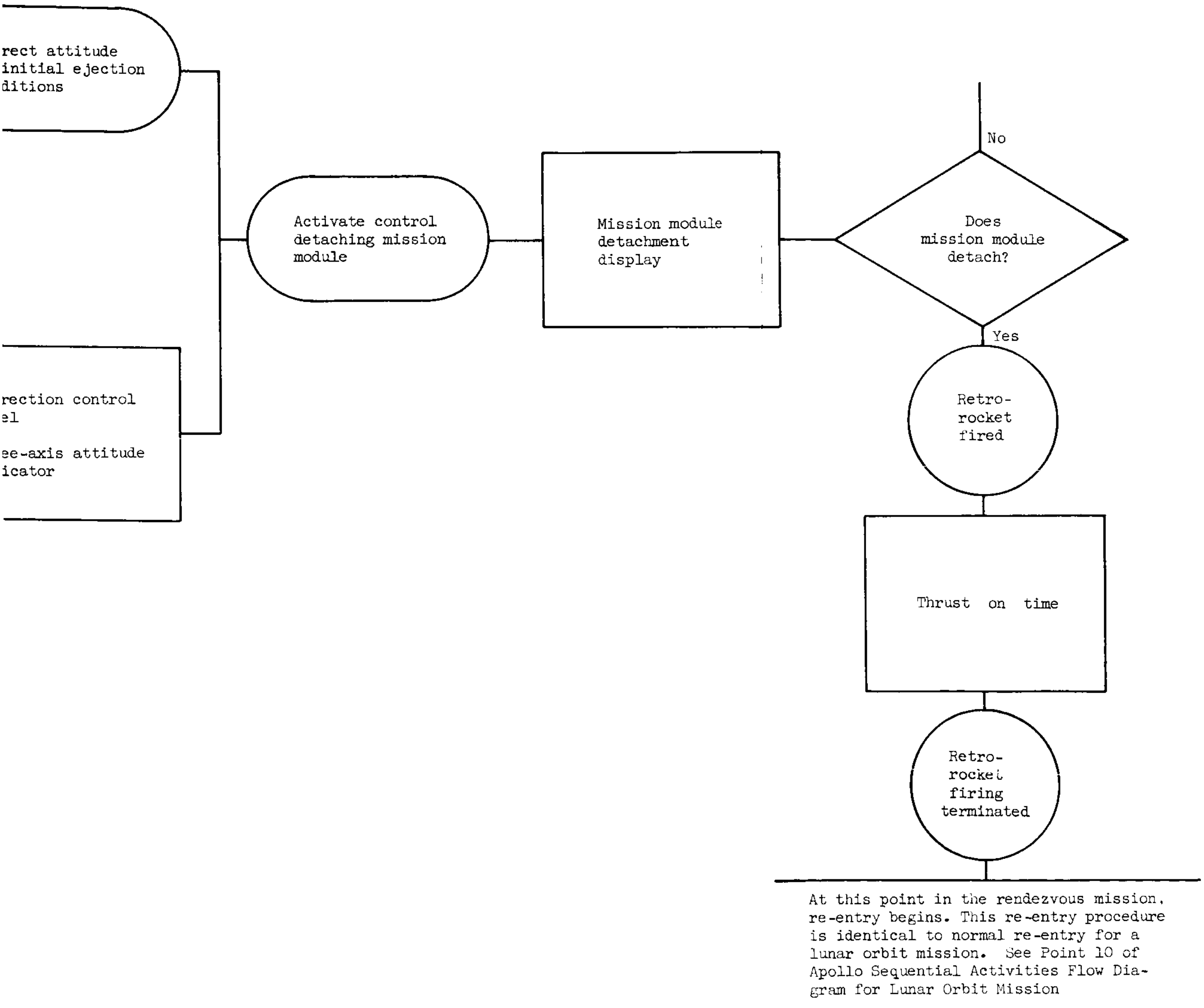

Antennas are erected
Indication of antenna erection
Rotate antennas to pick up target satellite signal
Strongest signal
Search TV screen to locate target satellite


Radar altimeter
Control vehicle position and velocity
TV camera position display
No
Is range within 200 ft?
Yes
Release infra-red seeking rocket
Rocket is fired, carrying cable behind
Rocket contacts target satellite


Activate control to reel in cable
Cable is reeled in, bringing the two objects in contact
At this point the rendezvous phase of the mission is complete. After the mission purpose has been completed, ejection from orbit begins
Program computer to calculate thrust parameters necessary to eject from orbit



Computer calculates thrust parameters
Computer readout
Program thrust parameters into correction display panel
Time to ejection = two minutes


rect attitude
initial ejection
ditions
rection control
el
ee-axis attitude
icator
Activate control
detaching mission
module
Mission module
detachment
display
No
Does
mission module
detach?
Yes
Retro-
rocket
fired
Thrust on time
Retro-
rocket
firing
terminated
At this point in the rendezvous mission,
re-entry begins. This re-entry procedure
is identical to normal re-entry for a
lunar orbit mission. See Point 10 of
Apollo Sequential Activities Flow Dia-
gram for Lunar Orbit Mission

lunar orbit, ejection from lunar orbit, trans-earth orbit, preparation for re-entry, re-entry and landing) and each of these phases examined to identify two things: 1) Those gross functions, accomplished by the crew, which are necessary to complete the mission; and 2) those crew tasks which must be accomplished in order to successfully complete each gross function.

An example of this would be the coast system's check (Task Analysis). The system check is a gross function which will be important in the determination of the probabilities of a successful mission completion. The system check is then broken down into the tasks necessary to examine the operation of the various sub-systems (communication system, propulsion system, guidance system, etc.).

The first column in the analysis, "Operational Phase", refers to the various stages of the mission, e.g., launch, coast, trans-lunar orbit, etc. The column headed "Lapsed Time" indicates the time that has elapsed since zero time (at launch). The "Information" column presents the knowledge required by the operator to perform the necessary tasks. The next column, "Reading, Present-Desired", shows the initial display readings (if any) and the display readings desired. The "Accuracy" column indicates the acceptable error tolerance in reading the displays. The column labeled "Controls" presents the manual control the operator uses to carry out the task, and the following column, "Operator", refers to the functions that man is required to perform. The last column, "Notes", is self-explanatory.

b. Utility

(1) Separation of crew tasks

The crew tasks were examined and delineated by logical function (e.g., navigation, control of vehicle, monitoring system status, etc.). On the basis of this separation, it was decided that there could be a division of the crew into three areas, with some degree of overlap existing for the purposes of (a) permitting continuous functions without disrupting the work-rest cycles and (b) compensating for the possible incapacitation of any one of the crew members.

The titles of the Apollo crew members are as follows: Pilot-Commander, Navigator-Pilot and Engineer-Scientist. The actual duties of these members are discussed in detail in another section.

(2) Crew seating and display design

Once the functions were designated and assigned, the information requirements obtained from the task analysis were listed for each crew member.

Next, the information requirements for an Apollo lunar orbit mission were translated into individual displays and the displays were then integrated into functional groupings, each grouping being placed at the pertinent crew member station.

When the first display considerations were established, a rough estimate of display area required per crew position was obtained. Then the available display area at each position was examined and a preliminary "best fit" obtained. This same process was repeated and refined as new information was added from the engineering personnel until display console designs were finalized.

All changes in the system were included into the task analysis as they appeared, and the analysis was utilized throughout the entire sequence of display design.

Thus, the task analysis played an integral part in both the positioning of the seats within the Apollo vehicle and the design of the displays. Without this type of analysis, seating positions and display design would have been less systematic, and seating positions might have required frequent changing with subsequent consideration of further factors.

(3) Control design and placement

Controls in the Apollo vehicle were designed by much the same method as the displays. First, lists based on the task analysis were compiled of both continuous and non-continuous control requirements (i.e., what to control, when to perform the central action). Then, these lists were examined as to the best type of control and the best position for the various control placements. Knowing the purpose of the control and under what conditions it would be used was instrumental in determining the type of control.

For example, it was determined from the continuous control list that although there were different means of controlling the vehicle (attitude rockets, aerodynamic control surfaces, main chute flap control) during different phases of the mission, the control parameters (roll, pitch, yaw) remained the same.

The conclusion as to the most feasible way of controlling the vehicle during these phases was to supply one 2-axis electric stick and one set of electric yaw pedals and allow the pilot to switch modes of operation whenever necessary.

The pull-rings on the sequencers for launch and landing are another example of using the information in the task analysis in the design of the controls. Pull-rings were utilized instead of buttons or toggle switches due to the possibility of the accidental activation of these latter-type controls during high-g maneuvers. Thus, by integrating and examining the information in each phase of the task analysis, a more efficient design was effected.

Again, in designing both the continuous and non-continuous controls, the task analysis was invaluable in making this study more systematic and comprehensive than it would have been without the use of the task analysis as a base and a constant reference source.

(4) Crew work load

Using the task analysis as a base, estimations were made of the times involved with accomplishing both monitoring tasks and non-continuous control tasks, and crew loadings were developed in terms of percentage of time occupied accomplishing each task. Thus, possible operator overload trouble points were eliminated and sequences modified when necessary.

c. Task analysis

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
Launch	Before Ignition	Vehicle ready to launch	No Go-Go		First stage enable button (Guarded pushbutton)	Commander notes condition of crew and equipment Series switch for launch	First stage enable light
	0 (Ignition)	Ignition has taken place			(None)		First ignition light
First Stage	to 100 sec	TRAJECTORY MONITOR	Ignite Light		Pilot-Commander has abort handle double action for positive control	Operator notes attitude control according to schedule Launch Monitor	Vehicle will roll to right heading Comparison of Aerodynamic & inertial readouts is an indication of Guidance System Man will probably initiate abort only on catastrophic conditions
		Pitch Attitude	90 deg-X ft	1.0 deg			
		Roll	30 deg-Launch	± 1 deg			
		Yaw	Directions 0-0				
		Altitude pressure	0-110,000 ft	$\pm 2,000$ ft			
		Altitude inertial	0-110,000 ft	$\pm 1,000$ ft			
		Time	0-100 sec	± 10 sec			
		q	0-6.00 psi	$\pm 5\%$			
		PROPULSION MONITOR					
		g profile, g_T	0-3 g	± 0.1 g		Monitor	
		Velocity	0-4,256 fps	± 1 sec			

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Time	0-100 sec	± 1 sec			
		COMMUNICATION Quality of Launch as monitored from pad Quality of radio communication			Volume Control	Note C Band Note S Band Note VHF	RCVR/XMTR turned on during countdown Martin Man Lunar Vehicle Studies Vol. I Part 1 (See pg. 4.22 for ground plot.)
		NAVIGATION Trajectory error velocity Injection computation is in process Range to earth Down range Cross range	seven in. scope display	$\pm 5\%$ of marginal $\pm 1\%$ ± 10 miles			Launch Site - Cape Canaveral Launch Azimuth - 117 deg
		ENVIRONMENTAL SYSTEM Cabin pressure-seal condition as reflected thru pressure differential	12 psi	± 0.5 psi		Monitors system operation	Cabin pressure stabilizes

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Check suit pressure	5 psi				
		0_2 partial pressure	155 mm				
		Humidity	50%				
		Cabin temperature	70 deg				
		Mission module pressure					
Second Stage	100 to 287 sec	Burnout - g staging (Separation light)	3----------0		Separation Backup D Ring Abort handle	Backs up staging	First Separate light Second Ignite light No backup of ignition
		Time		±10 sec			
		(Re-ignition light)					
		g	0------climb to 4.5 g	±0.1 g			
	170 sec	TOWER SEPARATION at 300,000 ft	Indication of sequence -- Tower - Separation"	±25,000 ft	Backup Tower Separation D Ring	Monitors and backs up	Tower Separate light
		MONITOR TRAJECTORY				Observe Launch Monitor zero meters	
		Pitch	39.8 deg - 3.4 deg	1.0%			
		Roll	Hold	±1.0 deg			

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Yaw	Hold	±1.0 deg		Notes departure from aerodynamic region	q may need to be computed rather than sensed
		Altitude-Inertial	110,000 ft - 615,000 ft	±1000 ft ±5%		Compares launch with schedule	q - is of use in abort decision re-entry goes to zero at 150 sec
		Time	100 - 287 sec	±10 sec			
		q	330.0 psi - 0	±5%			
		Flight path		1% nominal			
		MONITOR PROPULSION					
		g profile	0-4.5 g	±0.1 g			
		Velocity - inertial	4256-15,800 fps	±50 fps			
		Time	100-287 sec				
		COMMUNICATION					
		Quality of launch as monitored from pad			Volume control		Verbal communication a visual indication of quality is being considered
		Quality of radio communication					
		NAVIGATION					
		Trajectory error			Display selection	Monitors seven in. scope giving analog	See launch monitor

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Injection computation is in process Down range Cross range		±1% nominal ±10 units of nominal		Relation of performance to be expected	See altimeter
		ENVIRONMENTAL SYSTEM Cabin pressure (mission and command)	12.2 psi - 12 psi	±0.5		Monitor	
Third stage	287 to 775 sec	STAGING-IGNITION g	Second Separate Light on Third Stage Ignition 4.5 g-0 to build-up	±0.1 g	Abort handle Separation backup switch	Operator could control booster vehicle altitude in case of abort procedure	Second Separate Light Third Stage Ignition No ignition switch planned
		MONITOR TRAJECTORY Pitch Roll Yaw	3.4 deg -- 57.3 deg 0--0 0--0	±0.5 deg ±1.0 deg ±1.0 deg		Monitors zero meters Compares launch with schedule	MLV Vol. 1, part 2, Fig. 4.41, pg. 4.12

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Inertial Altitude	615,000 to 1,120,000 to 975,000	±50,000 ft ±5% nominal			MLV Vol.I part 2 Table 8.121 pg. 8.21 Project Apollo NASA working paper #1002, Nov. 9, 1960 pg. B.1
		Time	287 to 775 sec	±10 sec			
		Flight path		1% nominal			
		MONITOR PROPULSION					
		g profile	0 to 2.3 g	±0.1 g			Third Stage Cutoff light
		Velocity inertial	15,800 fps 25,500 fps	±50 fps			
		Time	287 to 775 sec	±10 sec	Third Stage Cutoff D Ring	"Third Stage Cutoff" Backup	
		Third Stage Cutoff light					
		COMMUNICATION					
		Quality of launch			Communications volume control		
		Quality of radio communication					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		NAVIGATION					
		Trajectory error		See note			Ref. Minneapolis-Honeywell Aero Rep. 61395-qR2. inertial requirements of boost Accuracy for earth orbit Attitude reading 0.01 deg elevation 0.01 deg, roll-- 0.058 deg Velocity along course 2.45 fps cross course 2.33 fps vertical 3.10 fps Position along course 318 ft cross course 363 ft vertical 731 ft
		Down range	315 mi. to 1630 mi.	±1%			
		Range to earth	615,000 to 1,120,000 to 975,000	nominal			
		Cross range		±10 miles			

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
Coast	20 to 70 min	MONITOR TRAJECTORY Flight path Pitch Roll Yaw		 $\pm 1\%$ $\pm 1\%$ $\pm 1\%$		Monitor free fall trajectory	Duration of coast variable dependent on position of moon
		Inertial altitude	975,000 ft 340,000 ft	$\pm 5\%$		Backup automatic system	Based on 775 sec to 1250 sec coast duration
		Inertial velocity	25,500 fps 26,500 fps	$\pm 5\%$			
		Time	20 to 70 min				See above
		SYSTEM CHECK Communication System (1) Output power (2) Modulation level (3) Supply voltages (4) Receiver gain control	 Normal Normal Normal Normal	 10% 10% 10% 10%		Abort decision based on both systems' operation	Check both systems of: (1) C Band (2) S Band (3) VHF (4) Deep space net (5) K_E

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Space Environment Systems					
		(1) Radiation	Normal expected			Abort decision based on accumulation versus probable total accumulation for total flight	Schedules of accumulation versus time for various trajectories on board
		(2) Meteorite Occurrence	Normal expected			Same	Same
		Coast Environmental Systems					
		Command module					
		(1) O_2 partial pressure	158 mm	5%		Detection of malfunctions which would cause abort	
		(2) CO_2 partial pressure	0-3.8 mm	±5%			
		(3) Cabin pressure	12.2 psi	±5%			
		(4) Cabin temperature	60 deg to 80 deg F	±10%			
		(5) Cooling system pressure					
		(6) Pressure flow rate					
		(7) Relative humidity	50%	±10%			
		(8) Electrical equipment temperature					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Mission module					
		(1) Total pressure	**12.2 psi**			**Detect leaks**	
		(2) Ventilation and circulation				**Check for circulation**	
		(3) Molecular sieve filter				**Check operation**	
		(4) Radiator coolant loop					
		(a) pressure	**50-60 psi**			**Check proper functioning**	
		(b) temperature					
		Propulsion Systems check					
		(1) Arm vernier and attitude propulsion system			**Switch**		
		(2) Monitor chamber pressures	**0**			**Check for leakage**	
		(3) Pressure tank pressure	**4500 psi**	**4500 - 4760 psi**		**Check for normal**	If reading is above maximum, mission must be aborted
		(4) Pressure tank temperature	**70 deg**	**70 to 100 deg**		**Check for normal**	
		(5) Propellant tank pressure	**60 psi**	**50 to 120 psi**		**Check for normal**	
		(6) Propellant quantity	**100%**			**Check for leakage**	

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		(7) Thrust chamber pressure	0			Check for leakage	
		(8) Propellant inlet temperature	0			Check for leakage	
		(9) Main tank pressure	15 psi	15 to 16 psi		Check for normal	
		Re-entry system check					
		(1) Computer				Run test program	
		(2) CRT system				Observe test program	
		(3) Autopilots				Abort decision based on 1. Loss of one computer 2. Loss of both CRT 3. Loss of both re-entry auto-pilot modes 4. Loss of both midcourse autopilot modes	Computer provides step or ramp input
		Hot Gas system check					
		(1) Fuel tank pressure	2800 psi				
		(2) Gas generator output					
		(a) Pressure	1200 psi	$\pm 5\%$		Check for fluctuation or drops	
		(b) Temperature		1400 deg			

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Electrical system check					
		(1) Battery check output voltage	28 volts				
		(2) Fuel Cell output voltage regulator	28 volts				
		Temperature	450 deg F	375 to 500 deg F			
		ΔP	2-6 psi				
		Bus voltage	28 volts				
		(3) Valve Tubing and Manifold check					
		ΔP					
		(a) Manifold	2-6 psi				
		(b) Hi-flow warning	2-6 psi				
		(c) Flight	On - off				
		(4) H_20 Separator and Temperature Regulator check			Off switch		
		Temperature	(1) 450-500 deg F	Steady			
	+20 sec		(2) 500-450 deg F	Drop	Switch to alternate	Abort decisions based on: (1) One H_20 separator malfunctioning (2) One manifold malfunctioning (3) One fuel cell or valve system malfunctioning	
		(5) Bus Flag & Load meter check	warning lights		Off nonessential switches		

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
COAST		INJECTION DECISION	Go No-Go Light				
		Vehicle Inertial (1) Time of injection (2) Injection duration (3) Thrust vector direction magnitude			Computer control	On board decision of lunar flight based upon system personnel and trajectory conditions	Feasibility of on-board decision should be studied Coast will be near one orbit
		Ground Computation (1) Time of injection (2) Injection duration (3) Thrust vector direction magnitude				Compare ground and on-board injection data conflict unresolved will cause abort	Coast time - dependent upon date and time of launch Longest possible coast time is 3.1 hrs. 0.01% velocity angle
		Comparison of data					0.01% speed error (Pg. 34 "Space Facts" General Electric)

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
INJECTION TO TRANSLUNAR TRAJECTORY	1250 to 1450 sec	MONITOR INJECTION			Abort handle		1250 sec - variable due to length of coast
		BURNING Third Stage Reignition Light					
		Roll attitude	0-0	±1 deg		Monitors flight control attitude	On board system is monitoring Saturn System
		Pitch attitude	-2 to +2 deg	±0.1 deg			
		Yaw attitude	0-0	±1 deg			
		Inertial velocity	26,500 fps 36,100 fps	25 fps		Monitors injection schedule	No operator control for burning cut-off
		Inclination angle	36 deg				
		g	0-2.3	±0.1 g			
		Injection accuracy (2)					
		(1) Velocity	36,100 fps	±25 fps (2)			
		(2) Altitude	340,000 to 400,000 ft (2)	10,000 ft			
		(3) Angle		0.05 deg			
		Time	1250 to 1450 sec		Saturn - third	Monitors cutoff (critical)	
		Position down range	12 deg W/ Longitude 16 deg S/ Latitude				

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		"Third Stage cutoff" light	3730-4, 700 mi down range	$^{+260}_{-100}$ miles			Depends on length of coast Third Stage cutoff light
SEPARATION FROM SATURN	1450 sec	SEPARATION Third Stage Separation light			Autopilot on rate damping mode Saturn suspension D ring	May need to control in case of unusual events	Time variable to length of coast phase Third Stage Separate light A/P controls will probably be: on-off Mode-damping -attitude hold -auto correction Reaction fuel valves
		Sequence-fire explosive bolts or separation rocket	Sequence light on		Backup switch for explosive bolts and separation rockets (if any) Periscope extended	Monitor and backup operation	Tumbling may take place on separation if explosive bolt malfunctions
		Lower periscope					
		g	2.3-0				
		Visually observe window (periscope or kinescope)			Manual attitude Controls-two axis Controller-Pedals	Observe separation of Saturn	

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Roll rate Pitch rate Yaw rate	0 0 0	±1 deg/sec ±1 deg/sec ±1 deg/sec	Altitude controls Rate Damper switch	Stops tumbling	
		MAINTAIN OPTIMUM ABORT ATTITUDE UNTIL TRAJECTORY AND SYSTEM HAVE BEEN PROVEN Monitor attitude COMMUNICATION Check injection via ground radio			Abort handle Manual attitude control system Volume control	Operator may manually override abort position	For abort purposes
TRANS-LUNAR ORBIT Beginning	(1600 sec) 25 min.	ORIENT TO SUN Roll Attitude Pitch Attitude Yaw Attitude	(Sun)	±3 deg ±3 deg		Orients to keep cooling surface away from sun	Nose of vehicle toward the sun

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		CHECK ENVIRONMENT			Mode select		
		Cabin pressure	12.2 psi	±1 psi		Switch to space environmental control system	
		Cabin temperature	70 deg F	±5 deg	Cabin fans		
		Cabin relative humidity	50%				
		Flight suit pressure	5 psi	±1 psi			
		Flight suit temperature	70 deg F				
		0_2 partial pressure	155 mm	±2%			
		Cabin cooling system					
		Radiation surface orientation (roll angle)			Attitude control	Vehicle attitude controlled for radiation cooling surface orientation	
		Open passage to mission module			Method of entering mission module with suit on Method of testing mission module	Manually opens passage after determining mission module condition	May need more checks than pressure alone After check man can remove suits

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		ESTABLISH COMMUNICATION					
		Extend antenna			Switch and slewing switches train antenna toward earth		
		Position antenna to earth signal				Points antenna to earth via signal strength	
		Turn on Deep Space Band			Deep space gear On-Off		Voice actuated communication
		CHECK INERTIAL INFORMATION				Determine whether information necessitates vernier correction	
		Position					
		Velocity					
		Check with radio information					
		Attitude-periscope					
		Nominal trajectory determination				Notes which nominal trajectory is established	Assume several nominals available
		Compare with radio link					Computer Input-output exchanges should be recorded

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
VERNIER INJECTION CORREC-TION	Up to 5 minutes after main injection	COMPUTE VERNIER CORRECTIONS					
		Time-duration	0-8 sec maxi-mum	±1 fps	Computer inputs		Extending duration of firing simpli-fies operator's task VIO-25 fps range
		Direction			Duration of fire		
		Set correction in			Direction of fire	Operator checks system with manual test program	
		Perform Trial					
		Determine (yes-manual) (no-auto)			A/P controls		
						Operator backs up operation	Is there need for automatic hold?
		PERFORM VERNIER CORRECTION					
		Operator restraints					
		Fire - g Time	0.-.0.1 g time on	±0.8 fps	Attitude control Fire button Autopilot mode select	Cutoff critical	(3) Table 8.147 MLV (Vol.2)
		Autopilot turned to high torque					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		RECOVER FROM VERNIER CORRECTION					
		Re-establish attitude			Attitude controls	Orient vehicle to normal trajectory attitude	
		Roll	Sun	±3 deg			
		Pitch	Sun	±3 deg			
		Yaw	Sun	±3 deg			
		Turn A/P to low torque			A/P mode select		Crew is free to move around
		Remove operator restraints					
NAVIGATION FIX		AUTOMATIC STAR TRACKER			CONTROL		Provide a shield remove control
		1. Remove tracker window shields switch					
	0	2. Switch tracker on and monitor following operations					
	-05 sec	3. Star select			On/Off button Auto button Star select Time-pressure button Auto button Star select		All lapsed time data is relative to start of fix
	06 sec	4. Read					
	11 sec	5. Select second star					
	12 sec	6. Read					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
	17 sec	7. Select third star			Time-pressure button		
	18 sec	8. Read			Auto button Star select		
	24 sec	9. Align platform			Time-pressure button		
		10. Select fourth star			Align button Repeat		
	30 sec	11. Read					
		12. Select fifth star					
	36 sec	13. Read					
		14. Select sixth star					
	42	15. Read					
	48	16. Check platform alignment					
		17. Switch to earth			Star tracker controls Auto-pilot controls		
	1 min	18. Automatic vehicle orientation			Normal backups		
	1 + 35 sec	19. Select east rim			Star tracker controls		
	1 + 36 sec	20. Read					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		21. Select west rim					
	1 + 42 sec	22. Read					
		23. Select east rim					
	1 + 48 sec	24. Read					
	1 + 53 sec	25. Select west rim					
		26. Read					
		27. Report 23-26 for 25 total readings					
	6 + 30 sec	28. Switch to moon track attitude			Star tracker controls		
		29. Automatic vehicle orientation					
		30. Select east rim					
	7 + 12 sec	31. Read					
		32. Select west rim					
	7 + 18 sec	33. Read					
		34. Repeat 30-33 for 25 readings					

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
	12 + 06 sec	MANUAL STAR TRACKER			Manual star tracker controls		Manual star tracking carried on simultaneously with automatic tracker
		1. Switch tracker					
		2. Select star					
		3. Position star in manual star tracker					
	0 + 12 sec	4. Push button to read					
	0 + 24 sec	5. Repeat 2, 3, 4 for star 2					
	0 + 36 sec	6. Repeat for star 3					
	0 + 40 sec	7. Align miniature platform			Inertial platform controls		
	0 + 48 sec	8. Display auto tracker reading and manual readings in 10-in. scope			10-in. scope display control		
		9. Select enter and insert good data into computer store			Computer control		

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		10. Position earth in manual tracker			Manual store tracker controls		
	1 + 29 sec	11. Select east rim					
		12. Read					
		13. Select west rim					
		14. Read					
		15. Repeat 11-14					
	2 + 36 sec	16. Repeat 11-14					
		17. Display auto tracker readings and manual readings in 10-in. scope			10-in. scope display control		
		18. Select, enter and insert good data into computer store			Computer controls		
		19. Position moon in manual tracker			Manual star tracker controls		
		20. Select east rim					
		21. Read					
		22. Select west rim					
		23. Read					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		24. Repeat 20-23					
		25. Repeat 20-23					
	6 + 30 sec	26. Display auto tracker readings and manual readings in 10-in. scope			10-in. scope display controls		
		27. Select, enter and insert good data into computer store			Computer control		
	12 + 12 sec	TRAJECTORY ERROR DETERMINATION					
		Select computer program to compute separate trajectories based on (1) Auto system (2) Manual data (3) Radio guidance data (4) Radio backup data and compare with nominal trajectory			Computer controls 10-in. scope display controls		
	13 + 12 sec	Read out errors on 10-in. scope			10-in. scope display Display controls		

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Determine most probable accurate error data					
		Enter and insert into computer			Computer control		
	21 min	Program computer to determine (1) Velocity correction (2) Time of correction (3) Duration of correction			Computer control	Navigator determines (1) If correction is necessary (2) Which nominal to select (3) Optimum timing (4) Is abort necessary	
		Program computer to compare and display selected corrections			Computer controls		
	22 + 12 sec	Communicate with ground, supply data and receive confirmation of computation			Communication controls		
	28 + 0 sec	Check On-Board Guidance and Control Systems			All		

~~CONFIDENTIAL~~

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
	40 + 0 sec	Crew prepares for correction					
	52 + 12 sec	Manually controlable correction attitude			Manual attitude system controls		
	52 + 49 sec	Set and monitor time display			Timer controls		
	52 + 54 sec	Select, set and monitor thrust control			Compute thrust controls		
ANALYSIS OF NAVIGATIONAL INFORMATION		DETERMINE relation of information to nominal track		Less than $\pm$200 mi.	Slide projector	Switches to display recommended procedure or instruction	
		Position Velocity Time			Seven-in scope display controls	Switches to display radio and inertial information to analog CRT display	
		Analysis of information as to accuracy and reliability			10-in. scope display controls	Introduces data routine to computer and calls for data analysis readout on 10-in. scope (10-in. scope monitors printer readout)	

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Make decision as to: (1) Continue as is (2) Make navigation fix (3) Make correction or abort					
	60 + 0 sec	MAKE MID-COURSE CORRECTION			Fire button Ignition shut-off	Pilot will back up and aid to control authority	
		Turn autopilot			Autopilot control	Pilot will introduce step to check autopilot recovery and operation	
		Assume attitude Roll Pitch Yaw	To computed value	± 1 deg	Vehicle attitude controls Ready-arm System 1, System 2, Select	Switch to correction attitude reference	Alternate systems can be proposed
		Turn on manual backup system					Attitude with respect to thrust vector is important
		Fire time	60 fps maximum 500 minimum 10 sec	± 1 fps			
		Main attitude g	3 to 20 sec 0-3 g to 8 fps^2				

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Angular rates Roll Pitch Yaw	 0 0 0	 ± 0.1 deg/sec ± 0.1 deg/sec ± 0.1 deg/sec			Angular rates are prime information in manual control
	63 + 14 sec	Fire time	60 fps maximum 500 minimum 10 sec	± 1 fps			
		Main attitude g	3 to 20 sec 0-3 g to 8 fps^2				
		Recompute BAKER correction impulse to correct for ABLE impulse error if necessary			Computer controls and thrust control		
		Make BAKER correction at BAKER time			Computer controls and thrust control		
		SYSTEM COMPONENT CHECK					
		Environment					See MLV Vol. 1, Part 2, pg. 8.142 for possible indications for other parameter

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		(1) Total cabin pressure	12 psi	± 1 psi	Suit temperature Physical Information		7 and 8 may not be necessary
		(2) Humidity	50%		Decompression (Pressure temperature)		
		(3) Cabin Temperature	70 deg	Range - 50 deg F - 80 deg F	Repressurization (Pressure temperature)		
		(4) Partial pressures (O_2, CO_2)	O_2 - 150 m	O_2 - ± 2.0% CO_2 - ± 1.0%	Launch O_2 Fans		
		(5) Trace gases			Snorkel Total Pressure setting Suit fan neutral Gas pressure setting Cabin fan molecular Sieve regenerate		CO_2 Two systems (1) Molecular sieves (2) LiOH
		(6) O_2 and N_2 Reserves					
		(7) Radiation Accumulation	Accumulation rems				
		Cooling					
		(1) Pressure in coolant loops			System selector		

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		(2) Temperature in coolant loops					
		(3) Attitude orientation			Attitude control		Keep coolant coils away from sun
		Electrical			Bus Select		
		(1) Generators			20 position selector check switch		
		(2) Fuel cells (voltmeters and ammeters)	28 volts		Cell select override (2)		
		(3) Warning lights	<u>Off</u> except in malfunction		Press-to-test lights		
		Water Recovery					
		(1) Normal			On-off switch (Mission sequence select) capsule		
		(2) Malfunction					
		(3) Water reserve indicator	30 pounds				
		Communication telemetry					
		(1) Select			Communication system select		

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		(2) C-Band			Volume control		
		(3) Telemetry			Telemetry Override system Select		
		(4) Intercom			Press to talk Intercom (1) On-off (2) Volume		
		(5) Antenna			Antenna position		
		(6) Deep space radio S-band					
		(7) Communication key board					Communication key board store message for burst transmission
Prepare For Lunar Injection	73 hrs	Navigation Fix	Previous navigational fix		See navigation fix, same	Observe moon via periscope or other system	Also use star occultation system on navigation check
		(1) Check platform alignment					
		(2) Perform position fixes					Accurate operator lunar fix is possible

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		(3) Compute position velocity	From nominal	$\pm$200 miles less than 20			
		(4) Correct navigational computer					
		Decide whether lunar orbit or landing is to be attempted					
		(1) Compute approximate required injection				Decide feasibility of lunar orbit a. Trajectory desired b. Guidance, quality, and reliability c. Energy stores (sufficient) d. State of crew	
		(2) Note system conditions (a) Environment (b) Radiation (c) Fuels					
		COMPUTE LUNAR INJECTION			Computer operation		
		(1) Enter desired moon altitude	1000 mile orbit	$\pm$200 mile		May select orbit altitude	
		(2) Determine					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		(a) Attitude (b) Time of firing (c) Duration of firing (d) Thrust level					
		(3) Enter trial solution into computer					
		(4) Report to ground					
		PREPARE EQUIPMENT					
		(1) Position vehicle in attitude			Attitude Controller	Vehicle attitude relates reference	System reference must be switched to moon, attitude reference to thrust control
		(a) Roll		± 1 deg			
		(b) Pitch		± 0.5 deg			
		(c) Yaw		± 1 deg			
		(2) Select high torque manual			Autopilot controls		
		(3) Fire ullage rockets			Ullage switch		Ullage impulse t_b 6 to 10 sec/start

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Propulsion			Feed valve over-ride		
		(1) Check supply	2400				
		(2) Feed valve condition					
		(3) Pressure					
Injection Into Lunar Orbit	Perise-lenium Point	MONITOR IN-JECTION					
	84.5 hrs	Ignite (timing) main drive rockets		± 1 second (critical)	Same as for injec-tion to translunar trajectory plus Injection data a. Thrust level b. Duration c. Time d. Angular orientation		Inject occurs at 28 deg past line connecting earth and moon centers (MLV, pg. 4.27 of Vol. I, part 1)
		Roll attitude Roll rate	Injection 0	± 0.1 deg ± 0.1 deg/sec	Autopilot a. Manual auto		Angular rates are prime information for manual control
		Pitch attitude Pitch rate	Attitude 0	± 0.1 deg ± 0.1 deg/sec	Propulsion a. Ignition b. Ullage Rockets c. Main and auxiliary valve		

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Yaw attitude Yaw rate	1000 mile orbit	±1 deg ±0.1 deg/sec			
		Inertial velocity	6530 fps. Add retro of 2700 fps maximum Yields (3830 fps)	±2.5 fps			1000 mile orbit
		g	0-1 g				
		Injection					±2835 fps for 50 mile
		(1) Period (2) Angle	10,000 ft 5.35 hrs				
		Time of burning	650 sec				50 mile orbit minimum 2750 fps maximum 3150 fps
							Thrust period 1 maximum burning time 650 sec Acc. ±25 fps Vel. after inj. 5350 orbital period 1.95 hours
Lunar Orbit		RECOVERY FROM INJECTION					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Roll rate	0	± 0.1 deg/sec	Reaction controls and autopilot damper	Stops perturbations Change vehicle reference to moon	System and attitude reference are with respect to moon
		Pitch rate	0	± 0.1 deg/sec			
		Yaw rate	0	± 0.1 deg/sec			
		ORIENT TO MOON					
		Assume moon vertical reference				Decide orientation moon vertical or inertial	Guidance System will switch to Lunar vertical reference
		Roll attitude	0	± 1 deg			
		Roll rate		± 0.1 deg/sec			
		Pitch attitude	Level	± 1 deg			
		Pitch rate		± 0.1 deg/sec			
		Yaw attitude	0	± 1 deg			
		Yaw rate		± 0.1 deg/sec			

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		TURN ON SUR-VEILLANCE EQUIPMENT			(Not Firm) 1. Cameras (a) Stereo (b) Wide-Angle (c) Conventional 2. Infrared 3. Radar 4. Spectroscopy 5. Radioactivity		Specific scientific mission to be determined at a later time
		CHECK-ATTAINED ORBIT					
		Altitude	1000 miles	$\pm$10,000 ft			
		Velocity	3830 fps	$\pm$25 fps			Lunar refer-ence
		Angle	Level with moon	$\pm$1 deg			
		Guidance check					
		(1) Periscope or kinescope					
		(2) Inertial equipment					
		COMPUTE VERNIER CORRECTIONS					Follow same procedure as used in vernier correction of translunar injection

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		PERFORM VERNIER CORRECTIONS			Same as for translunar orbit	Lunar, gravity anomalies, state of computation, etc. Make multiple corrections probable	Four corrections are anticipated
		ΔV	10 fps minimum 25 fps maximum		Attitude controls		
		Position			Fire button		
		Fire					
		(1) Acceleration	0-3 g to 8 fps^2				
		(2) Time duration	4 - 10 sec maximum				
		Reorient to moon (local vertical)			Attitude controls periscope or kinescope	Decide orientation moon vertical or inertial	Major research activity taking place
		Roll attitude	0	± 1 deg			
		Roll rate		± 0.1 deg/sec			
		Pitch attitude	0	± 0.5 deg			
		Pitch rate		± 0.1 deg/sec			
		Yaw attitude	0	± 1.0 deg			
		Yaw rate		± 0.1 deg/sec			

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
Lunar Orbit	1 1/2 Orbit 8 hrs	NAVIGATIONAL FIX					
		Visual projection to moon surface			Attitude controls autopilot radio equipment, radar equipment	Decides whether a navigation correction is necessary Checks Radar/ Radio Alt	Fix on moon surface features to establish accurate readings
		Radio Altimeters Radar		±10% of nominal			
		Star Tracker					
		Compare inertial guidance data to observed data					
		Correct inertial System if necessary					
		MAINTAIN NOMINAL ORBIT; VERNIER CORRECTIONS					Total-100 fps maximum thrust cutoff error 1.0 fps
		Monitor trajectory errors					
		Performs same as for mid-course corrections					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
Select and Prepare for Ejection From Lunar Orbit		MONITOR LUNAR SURVEILLANCE EQUIPMENT Attitude maneuvers may be required			Manual attitude controls	Experiments with various gains and magnifications	
			Same as Item 3 and 4 on Page II-116				
		CHECK PROPULSION SYSTEM Tank pressure and temperature Tank supply Feed valve condition Solenoid temperature	1200 Lb		Manual override of vent valve		
Injection To Transearth Trajectory		MONITOR EJECTION Ignite (timing)		± 1 sec (critical)	Ignition switch same as previous injection	Starts ignite	Eject takes place 28 deg before earth/moon line MLV pg 4.26 of Volume I, Part 1

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Roll attitude	0	$\pm$1.0 deg		Attitude with respect to ejection thrust vector	Assumption: manual control backup
		Roll rate		$\pm$0.1 deg/sec			
		Pitch attitude	0	$\pm$0.5 deg			
		Pitch rate		$\pm$0.1 deg/sec			
		Yaw attitude	0	$\pm$1.0 deg			
		Yaw rate		$\pm$0.1 deg/sec			
		Inertial velocity	3830 fps 2750 fps 6580 fps	$\pm$25 fps			Moon escape velocity
		g	0-1 g				
		Time of burning	0-650 sec maximum	$\pm$1 sec	Operator shutoff	(Monitors cutoff) Leaks in combustion chamber or equipment	Assumption: manual control backup
		Propulsion monitoring					
Transearth Orbit Beginning		RECOVERY FROM INJECTION					
		Roll rate	0	$\pm$1 deg/sec	Attitude control	Stops perturbations	
		Pitch rate	0	$\pm$1 deg/sec			
		Yaw rate	0	$\pm$1 deg/sec			

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Roll attitude	0	±3 deg	Attitude control	Reorient to sun	System changes to trajectory orientation
		Pitch attitude	0	±3 deg		Attitude reference changed	
		Yaw attitude	0	±3 deg			
		COMMUNICATION					
		Check re-establishment			Antenna alignment		
		CHECK INERTIAL INFORMATION					
		Position		Desired 15 nautical miles 40 nautical miles maximum		Determines whether information necessitates vernier correction	MLV, Volume I, Part 1, pg. 8.269
		Velocity		±25 fps			
		Check with radio					System should be accurate (critical)
		Attitude Periscope or Kinescope					

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Choose nominal trajectory					Dependent upon accuracy at injection
		COMPUTE VERNIER CORRECTIONS					Same as injection into translunar orbit
		Time duration			Computer controls		
		Direction					
		Set in corrections					
		Perform Trial					
		Determine yes-manual no-automatic					
		PERFORM VERNIER CORRECTION			Same as for translunar orbit		
		Attitude				Orient to thrust vector	
		(1) Operator restraint					
		(2) Fire	25 fps maximum	± 1 fps	Attitude control fire button		Four corrections are anticipated

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Acceleration	0-3 to 8 fps time on				
		Time		1 second			
		Autopilot turned to high torque			Autopilot mode select		
		RECOVER FROM VERNIER COR-RECTION			Attitude control		
		Resume normal orbit attitude					
		Autopilot turned to low torque			Autopilot mode select		
		Remove operator restraints					
	2 1/2 days	SYSTEMS CHECK					Same as trans-lunar orbit
Transearth Prepare for Re-entry		ESTABLISH EN-VIRONMENT FOR RETURN					
		Suits					
		Stores cooling	408 lb water				
		Re-entry g limit					

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		NAVIGATION FIX					
		PREDICTION OF RETURN					
		Perigree altitude		± 20 mile	Display computer controls	Match tactics with situation to arrive at best solution	
		Perigee time		± 30 mile			
		Orbital inclination		± 0.1 deg			
		Prediction of result of tactics					
		COMMUNICATION					
		Estimate arrival				Ground monitoring may help in estimation	
		Landing area					
		SELECT RE-ENTRY MODE			Selection of modes	Sets in control-aims	
		PREPARE FOR MISSION CAPSULE SEPARATION					
		Close passage way					

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Separation firing			Capsule separation switch	Backup observe separation	Separate from Mission Module
		Separation velocity	0-10 fps	±1 fps			
		Extend control surfaces to initial position			Flap system select		
		Check control surface operation			Flap control		
		ESTABLISH RE-ENTRY					
		q	Maximum 650 lb/ft^2 occurs at 174,000 ft velocity 35,000 fps		Reaction controls attitude	Establish and maintain attitude waiting for indication	
		Inertial altitude Pressure altitude	400,000 ft 80,000 ft	±5 miles ±1000 ft	Initial conditions		
		Attitude			Aerodynamic surfaces		
		Roll		±1 deg			
		Yaw		±1 deg			
		Pitch		±0.5 deg			

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Angle of attack		$\pm 1/2$ deg	Flap control	50 seconds after 400,000 maximum heating encountered	Attitude must be switched to earth reference
		Flight path		± 0.1 deg	Flight control select	Manual flight possible	Navigational system must be computed with respect to earth
		Sideslip		1/2 deg		Fly schedule or fixed value of α for re-entry trajectory control	X-15 and Dyna-Soar use α based control systems
		Temperature	Maximum +3200 deg F				
		Heating rate					Zero α used for no lift phase of flight skip control
		g	0-10 g maximum less desired				
		Velocity	35,000 Mach 1 to 1.5				
		LANDING PREDICTION					

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Latitude	±10 miles touchdown		Display select	Select landing pattern display for CRT'S	
		Longitude					
		Radio Communication			Radio mode		
		Radar					
		Course made good		±0.5 deg			
		EQUIPMENT MONI-TOR					
		Cooling stores	408 lb water				
		Cooling equipment					
Landing		DAMPING MONITOR DESCENT	±1/2 deg/sec		Flap controls		
		Pressure altitude	100,000 to 80,000 ft	±1000 ft			Drogue Chute Deploys at 80,000 ft
		DROGUE CHUTE DEPLOY	80,000 ft	±1000 ft	Backup D rings	Backup drogue chute deploy	
		Descent speed	400 fps				
		Pressure altitude	80,000 ft 15,000 ft	±1000 ft			

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Equipment check					
		(1) TV camera and display			Camera and scope controls		Check for operation
		Communications			Modulation select	Obtain wind data from ground for landing area	
		Initiate recovery systems					
		MAIN CHUTE DEPLOY	Off-On		Backup D rings	Backup main chute deploy. Select largest workable area free of obstruction down wind	
		Select landing site			TV camera controls		
		Monitor pressure altitude	15,000 - 29 ft				
		Chute flap indication					
		(1) Rotation		±5% of total opening	Two axis chute control stick	Steer and maneuver vehicle to safe landing site	Incorporated into flight display
		(2) Flap opening					

[redacted]

Operational Phase	Lapsed Time	Information	Reading Present-Desired	Accuracy	Controls	Operator	Notes
		Drag line altitude system			Drag line deploy backup	Check deployment of drag line through visual system	Weighted line 29 ft long fires rocket when weight touches ground
		Retro-Rocket fire drag line	29 ft		Backup D rings	Pull ring at 29 ft altitude to assure firing	
Touchdown (T)		LANDING ORIENTATION	Upwind	± 15 deg	Two axis stick	Steer vehicle into wind	To reduce lateral velocity to a minimum
		ACTIVATE RECOVERY SYSTEM			Recovery control		
		STRUCTURAL TEMPERATURE	Cool				Wait for vehicle to cool to safe temperature

[redacted]

b. Discontinuous control analysis

Based on the task analysis presented, a discontinuous control analysis was conducted. The discontinuous control analysis involves the determination of the time required by the operator to monitor displays and panels, check systems, and switch, communicate and perform all other discrete events. The time requirements are established by either experiment, extrapolation from previous data or by relating activity to human information processing rates. In the case of Apollo the discontinuous analysis used both the task analysis and the display-control configuration as a basis.

The activity analysis determines when an operator action or information exchange takes place and how long it takes for each event. Knowing these, the requirements for a given interval of time can be summed to determine what amount of time the operator must devote to specific functions.

The preliminary workspace and equipment recommendation provides the discontinuous analysis with a tangible starting point. The value of the analysis is a function of the reality of the system definition. If the system changes or is better defined later, the analysis is in a form which can be modified.

The events of the discontinuous analysis and their order of occurrence are dictated by mission, equipment and safety requirements. The mission requirements demand that certain events must occur at a particular time. Each mandatory event is usually preceded and followed by ordered activity on the part of the operator. Other events and monitoring requirements can be predicted from the equipment and safety considerations. The result of these studies are operator workloads.

The frequency with which the operator must monitor a display can be established by considering the permissible error or limit in relation to the rate at which the parameter can approach the limit. The operator will need to observe the parameter often enough to be able to observe any display variation before it reaches a limit. The frequency of observation will vary with different phases of the mission, i.e., fuel quantity will be observed more frequently as the reading nears empty.

An example of determining display monitoring frequency is the case of monitoring CO_2 in a closed environment. A maximum CO_2 build-up rate would occur if the absorbing system failed entirely. In such a case, the rate of build-up would be dependent upon the volume of air involved, and the operator's CO_2 output. CO_2 tolerance limits are well established, and a safe level can be specified. Given these conditions, a rate of monitoring of the CO_2 indicator can then be established.

The problem is to then determine how much time will be spent as a result of a given event. The method used makes use of information theory and the established data of experimental psychology. Correlation of estimates derived by this method and actual experimental data has proven very encouraging. In handling the discontinuous events by information theory, each event is described in terms of information content, i.e., bits of information. The amount of information will depend upon the accuracy required of the reading, the display presentation, and the past history of the instrument scan. Voice communication can similarly be classified and assigned information quantity.

Determining the amount of time each event will require will then depend upon the rate at which man can handle this information, or his "channel capacity". Experimental data related to man's information handling capacity establish empirically channel capacities for man, which are then applied to the type of information inherent in the event. In practice, this has produced results which correspond to data obtained by conventional methods.

In the Apollo analysis the following aspects of the mission were chosen for discontinuous analysis: Launch, Coast during 3rd stage shutdown, Orbit monitoring, Navigational fix, Mid-course correction, Injection into lunar orbit, Re-entry and Landing. The results of these discontinuous analyses are summarized in Table 1-7. The operator workload is presented in Table 1-8.

C. CONTRIBUTION & UTILITY OF MAN IN APOLLO

In the course of conducting the analyses of the crew's functions on Apollo, it became evident that the utilization of the crew also contributed directly to the system.

One method of describing this contribution is to merely list the involvement of the crew with the spacecraft subsystems. Such a list is presented in Table 1-9, which indicates the specific tasks that the Apollo crew perform in the guidance, communications and electric power subsystems.

We were also concerned with attempting to quantitatively demonstrate man's contribution to each subsystem, either in terms of weight, power, reliability, flexibility, accuracy or cost. Quantification of man's contribution is possible through the comparison of subsystems which include or exclude man as an integral component.

Three methods of quantification reliability, weight and power analyses of subsystems, have been considered. A number of subsystems were analyzed with and without man as an integral part of the system.

1. Reliability Analyses

a. Method

Man's contribution to the reliability of a subsystem is due to three factors:

TABLE 1-7

Summary of Discontinuous Analysis Operator Workloads

Phase	Discontinuous work load (% of one man's total capability)	
Launch	Pilot/Commander - 57% Nav/Pilot - 53% Eng/Sci - 22%	
Coast during third stage shutdown	Special system checks prior to lunar injection (Time required at 100% activity) Pilot/Comm - 27.17 min Nav/Pilot - 32.17 min Eng/sci - 15.34 min	
Navigation fix	Pilot/Commander - 78% Nav/Pilot - 30%	
Mid-course correction	Pilot/Commander - 61% Nav/Pilot - 2%	
Injection into lunar orbit	Pilot/Commander - 26% Nav/Pilot - 30%	
Re-entry	(1 hour prior to Initiation) Pilot/Commander - 38% Nav/Pilot - 36% Eng/Sci - 20%	(5 min prior to Initiation) 16% 5% 35%
Landing	Pilot/Commander - 17% Nav/Pilot - 22% Eng/Sci - 2%	

TABLE 1-8

TOTAL WORK LOAD ESTIMATES

Percent of 1 Man's Capability

Mission Phase	P/C	N/P	E/S	Mission Module	Total
1. Launch	60	55	22		137
2. Coast during third-stage shutdown	60	80	40		180
3. Injection	70	100	20		190
4. Separation from Saturn	100	50	20		170
5. Trans-lunar orbit					
a. Beginning	60	70	25	10	165
b. Orbit	45	50	20	50	160
c. Nav fix	100	95	15	-	210
d. Mid-course correction	61	100	30	-	191
e. Injection to lunar orbit	70	70	25		165
6. Lunar orbit	75	100	25	100	300
7. Injection to trans-earth orbit					
8. Trans-earth orbit		(Same as Trans - Lunar)			
9. Re-entry					
a. 1 hr prior period	85	65	35		185
b. 5 min prior period	60	45	50		155
c. Re-entry	80	65	25		170
10. Landing	65	60	15		140

TABLE 1-9

Summary of Man's Functions in

Apollo Spacecraft Subsystems

Guidance

Select guidance programs

Control vehicle attitude

Switch on automatic guidance routine

Select correction times

Select aim points

Weigh ground link information

Weight and read in manual guidance data

Select back-up guidance mode

Select checkout programs

Slew manual tracker

Communications

Voice communication

Switch from VHF to S-band communication

Switch off C-band beacon

Switch off DSIF and S-band beacon when space craft is behind moon

Select onboard tapes for transmission

Select guidance data for transmission

Rotate antennas for optimum reception

Switch to K_E band

Transmit special messages during re-entry

Switch on HF recovery beacon

Electrical Power

Switch fuel cells in case of drop in output

Start battery charging system after battery is used

Switch from fuel cell bus to recovery bus

Switch on recovery power unit

(1) Simpler, and therefore, more reliable equipment can be used because of the inclusion of man.

(2) Redundant equipment is utilized on a standby basis, whereas without man, active redundancy would be required in some cases. The difference in reliability due simply to these two procedures is, however, small. Standby redundancy is most advantageous during a failure when the standby equipment can be used until the failed module is located and replaced.

(3) Man, due to his utilization in the subsystem, replaces certain equipment such as sensing devices, programmers, comparators, computer and switching devices. Man can perform these functions under moderate acceleration loads and vibrations, and also while weightless. Without man, such equipment would have to be added to the subsystem and its reliability would be degraded.

An analysis of a subsystem can be performed by defining its reliability and mode of operation during each mission phase. A differentiation in reliability and mode of operation for the subsystem with man and without man must therefore be made.

b. Results

Man's contribution to the Apollo on-board guidance subsystem was determined using the method described. The guidance subsystem was analyzed with man and without man. Man's role was determined to be that of a sensing device, programmer, comparator, computer and switching device. The navigator-pilot, on the basis of his experience and judgment, utilizes the guidance subsystem outputs in a flexible manner, since he has complete information on desired and actual position, velocity, or attitude on which to base decisions of:

(1) If and when to abort.

(2) If and when to correct trajectories.

(3) If and when to change vehicle attitude.

The navigator can select aim points and correction times. He also checks and monitors guidance subsystem performance and operation, thus providing backup to the system. These monitoring and decision-making functions are difficult to translate into predictions of subsystem performance.

The analysis consisted of determining the:

(1) Time duration of each mission phase.

(2) Guidance subsystem operation during each mission phase.

(3) Reliability of each major component of the guidance subsystem.

Each of these steps is discussed more fully.

Time durations. An operational plan was specified for a 14-day Apollo lunar orbit mission, including about 6.9 days in lunar orbit for scientific purposes. The phases included: launch, third stage shutdown, injection into translunar trajectory, positional fixes, midcourse corrections, translunar transit, injection into lunar orbit, lunar orbit, ejection from lunar orbit, positional fixes, midcourse corrections, trans-earth transit, re-entry and landing.

Guidance subsystem operation. The equipment used during each phase of the mission was specified. A careful distinction was made between equipment used on standby versus active redundancy basis. Some equipment, used as standby redundancy by man, would be used on active redundancy without man (see Table 1-10).

Man's role in the guidance subsystem described implies that in the reliability analysis of the subsystem without man, man's reliability should be replaced by a small computer. This appears to be a conservative estimate of the reliability contribution of sensors, programmers and computers which would be necessary without man.

In analyzing the guidance subsystem without man, the following changes were made; another switch and digital computer were used in place of man, another inertial guidance platform was used in place of the backup platform and an additional automatic star tracker was used in place of the manual star tracker. Man's ability to check and monitor the performance of the guidance subsystem will also contribute to its reliability and accuracy but these contributions are not presently quantified and could not be used here.

Component reliability. An hourly failure rate was obtained for each major component of the guidance subsystem. A failure rate was assumed for man, since none was readily available for this type of task. The estimated failure rate of the communications subsystem was included, since this system has an important role in the guidance system during certain phases of the Apollo mission. The failure rates for the propulsion and attitude control systems were not included. Table 1-11 lists the hourly failure rates used in the reliability analysis. These failure rates are only estimates and might be considerably changed. They are used to compare the reliability of the guidance system with man and without man. It is the relative contribution of man which is of concern, not the actual reliabilities of the system or its major components.

TABLE 1-10

Summary of Estimates of Guidance Subsystem Operation Times

MISSION PHASE	DURATION (hr)	AIP %	MIP %	AIT %	MST %	GDC (2) %	COMM %
Ascent	0.22	100	100 A	0	0	100 A	100
Third stage shut-down and coast	1.33	100	100 A	0	0	100 A	100
Injection into trans-lunar trajectory	0.06	100	100 A	0	0	100 A	100
Trans-lunar transit	84.00	--	--	--	--	--	100
(1) Coast	66.00	100 P	100	0	0	2 A	--
(2) Position fixes (6)	3.00 ea	100	100 P	33	33 A	100 P	--
Injection into lunar orbit	0.03	100	100 A	0	0	100 A	100
Lunar orbit	165.95	--	--	--	--	--	50
(1) Coast	153.95	100 P	100	0	0	2 A	--
(2) Position fixes (2)	3.00 ea	100	100 P	33	33 A	100 P	--
(3) Scientific meas-urements (6)	1.00 ea	100	100 P	33	33 A	100 P	--
Ejection from lunar orbit	0.03	100	100 A	0	0	100 A	100
Trans-earth transit	84.00	--	--	--	--	--	100
(1) Coast	66.00	100 P	100	0	0	2 A	--
(2) Position fixes (6)	3.00 ea	100	100 P	33	33 A	100 P	--
Re-entry	0.28	100	100 A	0	0	100 A	100
Landing parachute descent	0.10	--	--	--	--	--	100

AIP - Astro-inertial platform
MIP - Miniature inertial platform
AIT - Astro-inertial tracker
MST - Manual star tracker
GDC - Guidance digital computer

COMM - Communications system

A - Active redundancy
P - Passive redundancy

The following equations were used:

Series components - $P = e^{-(f_A+f_B+. \ . \ . \ .+f_N)t}$ (1)

Two components in active redundancy - $P = e^{-f_At}+e^{-f_Bt}-e^{-(f_A+f_B)t}$ (2)

Two components in passive (standby) redundancy -

If $f_A = f_B$, $P = e^{-f_At(1+f_At)}$ (3)

If $f_A \neq f_B$, $P = \dfrac{f_Ae^{-f_Bt}-f_Be^{-f_At}}{f_A-f_B}$ (4)

Where

P = probability of zero failures to time t, and

f_A, f_B, f_N = hourly failure rates of components A, B, N.

The results of this analysis are shown in Fig. 1-1, which is a plot of the degradation of the guidance subsystem reliability with time. Since the graph cannot show the small fractional reductions in reliability for the very short operational phases such as position fixes, the curves appear fairly flat. It can be seen from this figure that the guidance subsystem with man achieves a reliability of .874, whereas without man the reliability of the subsystem is only .735. It should be pointed out that new estimates are continually being made of the values presented in Tables 1-10 and 1-11, especially Table 1-11. Therefore, the reliability figures presented only indicate the relative contribution of man to the Apollo guidance subsystem, not absolute values.

Fig. 1-2 presents the effects of redundancy upon the guidance subsystem without man and indicates that at least triple redundancy is required for a system without man to approach the reliability of a double redundancy system with man.

2. Maintenance and Weight Analyses

Another method of quantifying man's contribution to various subsystems is to consider the improvement in reliability of the subsystem due to human maintenance (Ref. 1). This problem is considered in the first part of this section. A number of mathematical models have been developed which quantify the increase in subsystem reliability when a maintenance capability is considered. The previous analysis did not consider the additional improvement in subsystem reliability due to man's ability to repair equipment. Repair is here considered to involve detecting, locating, and replacing a failed module. An improvement in the reliability of redundant equipment used on a standby basis

TABLE 1-11

Estimated Hourly Failure Rates for Major Components of Apollo Guidance Subsystem

Component	Hourly Failure Rate	
	During Coast and Transit	During Launch, Injection, Ejection, and Re-entry
Astro-inertial platform	0.000197	0.001973
Miniature inertial platform	0.000132	0.001315
Guidance digital computer	0.003970	0.039700
Astro-inertial tracker	0.000066	0.000657
Manual star tracker	0.000033	0.000329
Man (with self-correction)	0.000010	0.000100
Switches	0.000100	0.000100
Communications system	0.000042	0.000417

is possible provided; spare modules are available; functional (not necessarily physical) replacement can be effected; the failure can be detected, located and replaced before a second failure occurs; and the crew has sufficient time, free from the pressure of other duties, to devote to maintenance (Ref. 2).

Thus, it can be demonstrated that the ability to perform maintenance, and consequently improve reliability, is dependent upon equipment failure rates and time required to repair a failure. The second part of this section considers the related problem of the relationship of increased reliability due to maintenance to increased weight due to spares.

a. Manned versus unmanned maintenance

The problem of manned versus unmanned maintenance is fraught with conceptual as well as quantification difficulties. The latter at present are the more difficult, i.e., actual failure rates of modules are not presently established.

No comprehensive model seems feasible at this time. The best that can be done is to indicate the assumptions which have been incorporated into various mathematical models. Three types of failures have been assumed.

Type A--random failures (Poisson distributed). This type of failure is explicitly considered in our models (hourly failure rates).

Type B--failures caused by severe environment (vibrations and shock of launching, high humidity, etc.). These failures are considered by multiplying the basic hourly failure rate by an appropriate environmental modifier.

Type C--failures caused by old age. Given adequate test and storage, and considering that the maximum design duration of the mission is short, this factor does not seem too important. It is not handled in the models.

In considering manned versus automatic maintenance, several classes of maintenance seem plausible:

Class I--Certain modules can only be plugged in, and is accomplished by man. Spares are not available for these modules for the automatic maintenance system. A time (r) associated with repair by man (detect, locate, and replace) is pertinent.

Class II--In some cases plug-in modules may be inherently lighter than the corresponding elements used by automatic maintenance systems (e.g. a transistor module is lighter than a transistor module, plus fail-safe monitor and switch).

Class III--System backup is considered to be the case where a module is available to be plugged in or switched on as a backup to several active modules. The difference between manned and automatic maintenance systems is the weight and unreliability penalties imposed by sensors and switches of the automatic system.

Class IV--In some cases it may be impossible to design the circuitry of an automatic system to allow system backup. Hence, the automatic system with a spare module for each module requiring backup (modular backup) must be compared with the manned system using one module as a backup for several active modules (system backup).

Under any of these classes of maintenance, or combinations of classes, the expected human performance is superior to automatic (unmanned) maintenance.

b. Mathematical models

Model 1. The first model presents a method, previously derived by others and in common use in reliability calculations, for calculating the reliabilities of actively and passively redundant components connected in series. The gain in reliability associated with maintenance Class I, i. e., repair by man involving a finite length of time (r) to repair, is derived.

Assume the probability of failure on the part of any single element in time Δt is approximated by $f \Delta t$ where Δt is "small", i.e. the probability of failure at a given time is independent of the past history.

Let $P_o(t)$ be the probability of zero failures having occurred during time, t.

$$P_o(t+\Delta t) = (1-f\Delta t)\, P_o(t) \tag{1}$$

$$P_o(o) = 1 \tag{2}$$

(1) can be rearranged to the form:

$$\frac{P_o(t+\Delta t) - P_o(t)}{\Delta t} = -f\, P_o(t)\,.$$

and taking the limit of both sides of this equation as Δt approaches zero we get:

$$\frac{dP_o(t)}{dt} = -f\, P_o(t) \quad \text{with} \quad P_o(o) = 1$$

and the solution:

$$P_o(t) = e^{-ft} \quad . \tag{3}$$

Let $P(\tau \geq \mu)$ be the probability that the time between failures (τ) is greater than μ. Accordingly $P(\tau \leq \mu)$ is the distribution function for the time between failures.

$$P(\tau \geq \mu) = e^{-f\mu}$$

$$P(\tau \leq \mu) = 1 - e^{-f\mu}$$

and $f(\mu)$ the probability density for the time between failures is given by:

$$f(\mu) = \frac{d}{d\mu} P(\tau \leq \mu) = f e^{-f\mu} \quad .$$

Let $\bar{t}$ be the average time between failures, which is the reciprocal of the failure rate.

$$\bar{t} = \int_0^\infty t f(t) \; dt = \int_0^\infty t e^{-ft} \; dt = 1/f \; .$$

Hence f is the failure rate.

We now define the reliability $R(t)$ to be the probability of zero failures during time t.

$$R(t) \underset{def}{\equiv} P_o(t) \; .$$

The reliability of two elements A and B in series is given by

$$R_{A \cap B}(t) = R_A(t) \cdot R_B(t) = e^{-f_A t} \cdot e^{-f_B t} = e^{-(f_A + f_B)\, t} \; . \tag{4}$$

The reliability of two actively redundant parallel elements A and B, where τ is the time required to repair a single element which has failed, is given by:

$$R_{A\cup B}(t) = 1 - \left\{ \int_0^r \left[\int_0^T f_A e^{-f_A u} f_B e^{-f_B T} \, du \right] dT \right. \tag{5}$$

$$\left. + \int_r^t \left[\int_{T-r}^T f_A e^{-f_A u} f_B e^{-f_B T} \, du \right] dT \right\}$$

$$- \left\{ \int_0^r \left[\int_0^T f_B e^{-f_B u} f_A e^{-f_A T} \, du \right] dT \right.$$

$$\left. + \int_r^t \left[\int_{T-r}^T f_B e^{-f_B u} f_A e^{-f_A T} \, du \right] dT \right\}.$$

Note that if $\tau = t$ we have the case where no repair capability is assumed. Let us denote this reliability by $R_{o\,A\cup B}(t)$.

$$R_{o\,A\cup B}(t) = 1 - \left\{ \int_0^t \left[\int_0^T f_A e^{-f_A u} f_B e^{-f_B T} \, du \right] dT \right. \tag{6}$$

$$\left. + \int_0^t \left[\int_0^T f_B e^{-f_B u} f_A e^{-f_A T} \, du \right] dT \right\}.$$

The improvement in reliability due to adding a repair capability is given by:

$$R_{A\cup B}(t) - R_{o\,A\cup B}(t) = \int_r^t \left[\int_0^{T-r} f_A e^{-f_A u} f_B e^{-f_B T} \, du \right] dT \tag{7}$$

$$+ \int_r^t \left[\int_0^{T-r} f_B e^{-f_B u} f_A e^{-f_A T} \, du \right] dT$$

$$> 0.$$

Evaluating Expressions (5), (6) and (7) we find:

$$R_{A \cup B}(t) = e^{-f_A r} + e^{-f_B r} - e^{-(f_A + f_B)\, r}$$

$$- \left[e^{-(f_A+f_B)\, r} - e^{-(f_A+f_B) t} \right] \left[\frac{f_A e^{f_B r} + f_B e^{f_A r}}{(f_A + f_B)} - 1 \right] \tag{8}$$

for $r \leq t$.

$$R_{o A \cup B}(t) = e^{-f_A t} + e^{-f_B t} - e^{-(f_A+f_B)\, t} \; . \tag{9}$$

$$R_{A \cup B}(t) - R_{o A \cup B}(t) = e^{-f_A r} - e^{-f_A t} + e^{-f_B r} - e^{-f_B t} \tag{10}$$

$$- \left[\frac{(f_A e^{f_B r} + f_B e^{f_A r})}{(f_A + f_B)} \right] \left[e^{-(f_A + f_B)\, r} - e^{-(f_A+f_B)\, t} \right] .$$

The reliability (probability of no failures at time t) has been derived for active redundancy of two elements, A and B, for the case where a failed component may be repaired in time r (expression (8), and for the case where it may not be repaired (expression (9). The gain in reliability effected by including the repair capability is given by expression (10).

The reliability of two passively redundant parallel elements A and B, where is the time required to repair a single element which has failed is given by:

$$R_{A\cup B}(t) = 1 - \left\{ \int_0^r \left[\int_0^T f_A e^{-f_A \mu} f_B e^{-f_B(T-\mu)} \, d\mu \right] dT \right. \tag{11}$$

$$\left. + \int_r^t \left[\int_{T-r}^T f_A e^{-f_A \mu} f_B e^{-f_B(T-\mu)} \, d\mu \right] dT \right\}$$

Note that if $r = t$ we have the expression for the case where no repair capability is assumed, again denoted $R_{o\,A\cup B}(t)$:

$$R_{o\,A\cup B}(t) = 1 - \left\{ \int_0^t \left[\int_0^T f_A e^{-f_A \mu} f_B e^{-f_B(T-\mu)} \, d\mu \right] dT \right\} \tag{12}$$

The improvement in reliability due to a repair capability being added is given by:

$$R_{A\cup B}(t) - R_{o\,A\cup B}(t) = \int_r^t \left[\int_0^{T-r} f_A e^{-f_A \mu} f_B e^{-f_B(T-\mu)} \, d\mu \right] dT \tag{13}$$

$$> 0.$$

Evaluating expressions (11), (12) and (13) we find:

$$R_{A\cup B}(t) = \frac{(f_A e^{-f_B r} - f_B e^{-f_A r})}{(f_A - f_B)} \tag{14}$$

$$- \frac{f_B}{(f_A - f_B)} \left[e^{(f_A - f_B) r} - 1 \right] \left(e^{-f_A r} - e^{-f_A t} \right)$$

for $A \neq B$, $r \leq t$.

$$R_{A\cup A}(t) = e^{-f_A r} + f_A r \, e^{-f_A t} \quad \text{for } A = B, \quad r \leq t. \tag{15}$$

$$R_{oA\cup B}(t) = \frac{(f_A e^{-f_B t} - f_B e^{-f_A t})}{(f_A - f_B)} \quad \text{for } A \neq B. \tag{16}$$

$$R_{oA\cup A}(t) = e^{-f_A t} + f_A t\, e^{-f_A t} = e^{-f_A t}\,(1 + f_A t) \tag{17}$$

for $A = B$.

$$R_{A\cup B}(t) - R_{oA\cup B}(t) = \frac{f_A f_B}{(f_A - f_B)} \left[\frac{(e^{-f_B r} - e^{-f_B t})}{f_B} \right. \tag{18}$$

$$\left. - \frac{(e^{-f_A r} - e^{-f_A t})}{f_A}\, e^{-(f_A - f_B)t} \right] \quad \text{for } A \neq B.$$

$$R_{A\cup A}(t) - R_{oA\cup A}(t) = e^{-f_A r} - e^{-f_A t}\left[f_A(t-r) + 1\right] \tag{19}$$

for $A = B$.

The reliability for passive redundancy of two elements has been derived for the repair case (expression (14) or (15) and for the non-repair case (expression (16) or (17). The case of $A \neq B$ is treated separately from the case of $A = B$. The gain in reliability due to repair is given by expression (18) or (19).

For the present let $R_a(t)$ denote $R_{A\cup B}(t)$ for the actively redundant case and $R_p(t)$ denote $R_{A\cup B}(t)$ for the passively redundant case. $R_p(t) - R_a(t)$ is the improvement in reliability effected by a change from active to passive redundancy.

$$R_p(t) - R_a(t) = \int_0^r \left\{ \int_0^T f_A f_B \left[e^{-f_A \mu} e^{-f_B (T-\mu)} - e^{-f_A \mu} e^{-f_B T} \right. \right. \tag{20}$$

$$\left. \left. - e^{-f_B \mu} - e^{-f_A T} \right] du \right\} dT + \int_r^t \left\{ \int_{T-r}^T f_A f_B \right.$$

$$\left. \left[e^{-f_A \mu} e^{-f_B (T-\mu)} - e^{-f_A \mu} e^{-f_B T} - e^{-f_B \mu} e^{-f_A T} \right] du \right\} dT$$

$$> 0.$$

$$R_p(t) - R_a(t) = \frac{f_B}{(f_A - f_B)} e^{-f_B r} - \frac{f_A}{(f_A - f_B)} e^{-f_A r} + e^{-(f_A + f_B) r} \tag{21}$$

$$- \frac{f_B}{(f_A - f_B)} \left[e^{-(f_A - f_B) r} - 1 \right] \left(e^{-f_A r} - e^{-f_A t} \right)$$

$$+ \left[\frac{f_A e^{f_B r} + f_B e^{f_A r}}{f_A + f_B} - 1 \right] \left[e^{-(f_A + f_B) r} - e^{-(f_A - f_B) t} \right]$$

Expression (21) gives the gain in reliability by using passive redundancy instead of active redundancy.

Model 2. An expression is derived for the reliability of a system of components whose failure rates may vary in time. The expressions are complicated by a need to consider whether the redundant components are in active or passive redundancy, and by not succumbing to the inexact approximation that the reliability of a redundant system during two separate time periods is the product of the reliability of the system during the first period times the reliability of the system during the second period.

Consider the calculation of the reliability, without repair capability, of a redundant system whose failure rates f_A and f_B are step functions of time, and where the system may be in active redundancy during part of its operation and in passive redundancy during the other part.

Let us assume that there are n time periods $t_1, t_2, \ldots, t_n$ where $t_1 + \ldots + t_n = t$, the total time of operation.

During each t_i the failure rates are constant and it is specified whether the system is in active or passive mode.

The reliability is given by:

$$R(t) = P_o(t_1) \ldots\ldots P_o(t_n) + \sum_{i=1}^{n} P_o(t_1)\, P_o(t_2) \ldots\ldots P_o(t_{i-1})\, C_i \qquad (1)$$

where

$$P_o(t_k) = P_{o_A}(t_k)\, P_{o_B}(t_k)$$ if the component is active during t_k

and

$$P_o(t_k) = P_{o_A}(t_k)$$ if the component is passive during t_k.

$$C_i = \left[1 - P_{o_A}(t_i)\right] P_{o_B}(t_i + \ldots + t_n) + \left[1 - P_{o_B}(t_i)\right] P_{o_A}(t_i + \ldots + t_n)$$

if the component is active during t_i.

$$C_i = \left\{ \int_0^{t_i} \left[\int_0^{T} f_{A_i} e^{-f_{A_i}\mu} f_{B_i} e^{-f_{B_i}(T-\mu)}\, d\mu \right] dT \cdot P_{o_B}(t_{i+1} + \ldots + t_n) \right\}$$

$$\therefore C_i = \frac{f_{A_i}}{(f_{A_i} - f_{B_i})} \left(e^{-f_{B_i} t_i} - e^{-f_{A_i} t_i}\right) P_{o_B}(t_{i+1} + \ldots + t_n) \text{ if } A_i \neq B_i,$$

and the component is passive during t_i.

$$C_i = f_{A_i} t_i \; e^{-f_{A_i} t_i} \; P_{o_B}(t_{i+1} + \dots . + t_n) \quad \text{if} \quad A_i = B_i \; .$$

and the component is passive during t_i .

$$P_{o_A}(t_k) = e^{-f_{A_k} t_k} \qquad P_{o_B}(t_k) = e^{-f_{B_k} t_k}$$

$$P_{o_A}(t_1 + \dots . + t_n) = e^{-(f_{A_1} t_1 + \dots . + f_{A_n} t_n)}$$

$$P_{o_B}(t_1 + \dots . + t_n) = e^{-(f_{B_1} t_1 + \dots . + f_{B_n} t_n)}$$

f_{A_i} = constant value of f_A throughout t_i

f_{B_i} = constant value of f_B throughout t_i

Model 3. This model presents the gain in reliability of a manned mode of maintenance over an automatic mode under the assumptions of maintenance Class IV, namely, the situation in which man may allocate available spares to the replacement of any pertinent module which may have failed. However, the automatic mode of maintenance requires a spare module for each module requiring backup.

The reliability of m elements in series, where the j th element has $n(j) - 1$ spares in standby redundancy is given by:

$$R(t) = \prod_{i=1}^{m} \left[\sum_{j=o}^{n(i)-1} \frac{e^{-f_i t} (f_i t)^j}{j!} \right] \tag{1}$$

where f_i is the failure rate of the ith element.

If m elements of the same type are in series and n spares are available to repair failures in any order that they may occur the corresponding reliability denoted by R_M (t) is given by:

$$R_M(t) = \sum_{j=o}^{n} \frac{(mft)^j \; e^{-mft}}{j!} \tag{2}$$

where f is the failure rate of a single element.

Expression (2) gives the reliability associated with a manned mode of maintenance, given n spares with which to maintain m like components.

If m elements of the same type are in series and n spares are available to repair failures, and allocated such that the j^{th} element has n (j) spares available ($\sum_{j=1}^{m} n(j) = n$) the corresponding reliability denoted by R_A (t) is given by:

$$R_A(t) = \max_{\substack{\sum_{j=1}^{n} n(j) = n \\ n(j) \geq 0}} \prod_{j=1}^{m} \left[\sum_{j=o}^{n(j)} \frac{e^{-ft} (ft)^j}{j!} \right]$$

$$= \left(\sum_{j=o}^{k+1} \frac{(ft)^j \; e^{-ft}}{j!} \right)^s \left(\sum_{j=o}^{k} \frac{(ft)^j \; e^{-ft}}{j!} \right)^{m-s} \tag{3}$$

where f is the failure rate of a single element and $n = km + s$

where $k = 0, 1, \ldots\ldots.$, and $O \leq s \leq m$.

Expression (3) gives the reliability associated with an automatic mode of maintenance in which n spares are fixed in component back-up in such a manner as to maximize the reliability of m like components.

If $n \leq m$,

$$R_M(t) - R_A(t) = e^{-mft} \left[\sum_{j=o}^{n} (m^j - n(n-1) \ldots . (n-j+1) \frac{(ft)^j}{j!} \right] \tag{4}$$

which is much greater than zero if m is large.

Expression (4) gives the difference between expression (2) and expression (3), i.e., the additional reliability associated with a manned mode of maintenance for a fixed number of spares.

Model 4. This model allows the calculation of the relationship between weight and reliability by a manned mode or by an automatic mode of maintenance. Under the assumptions of maintenance, Class III, i.e., the manned and automatic maintenance systems are equivalent except for the weight and unreliability incurred by the automatic system due to its switches and sensors.

Given a large number of identical modules n, it is assumed that a reasonable allocation of spares is one spare to m modules, where mft = 1 = expected number of failures.

n = number of identical modules, $m \leq n$
f = modular failure rate
t = time on

Given one spare for m modules:

$$R_A(t) = P_o(t) + \int_0^t mf\, e^{-mf\mu} \cdot e^{-f_s \mu}\, e^{-mf(t-\mu)} \quad d$$

$$= e^{-mft} + mf\, e^{-mft} \int_0^t e^{-f_s \mu} \quad d$$

$$= e^{-mft} \left[1 + \frac{mf}{f_s} \left(1 - e^{-f_s t}\right) \right]$$

$$\cong e^{-mft} \left[1 + \frac{mf}{f_s} \left(f_s t - \frac{f_s t^2}{2} \right) \right]$$

$$R_A(t) \cong e^{-mft} \left[1 + mft - \frac{mf\, f_s t^2}{2} \right] \qquad (1)$$

$$R_M(t) = e^{-mft} \left[1 + mft \right] \qquad (2)$$

$$R_M(t) - R_A(t) \cong e^{-mft} \; \frac{mf f_s t^2}{2} \qquad (3)$$

where:

- m = number of modules per spare; number of spares allocated is one per m
- f = failure rate of individual module
- f_s = failure rate of sensors and switches.

Expression (1) gives the reliability of the system with an automatic mode of maintenance and expression (2) gives the reliability of the system with a manned mode of maintenance. Expression (3) gives the gain in reliability of manned over automatic modes of maintenance. The difference in weight is, of course, equal to the increased weight of sensors and switches.

<u>Model 5 (Special case of Model 3)</u>. This model allows the calculation of the relationship between weight and reliability by a manned mode or by an automatic mode of maintenance. Under the assumptions of Class IV, i.e., the manned system has a spare module to back up several modules (systems backup), whereas the automatic system requires a spare module for each module requiring backup (modular backup).

A system is considered to have K supermodules, where the failure rate F_K, the number of modules N_K, and the time of use T_K are given for each K.

Each supermodule is split into $\frac{N_K}{n(K)} = m_k$ modules, where m_k is an integer for each K. n(K) represents the number of modular varieties and m_K represents the number of modules in the variety which are identical. It is assumed that spares will be allocated by man on a system redundancy basis at the modular level, whereas the spares of the automatic maintenance system can only be allocated for individual modular backup (Maintenance Class IV).

The failure rate f_K of each individual module within the K^{th} supermodule is assumed to be $\frac{F_K}{N_K}$. Without actual modular failure rates, this was the best assumption to make since $\sum_{i=1}^{N_K} f_K = F_K$. The reliability for the manned mode of maintenance is given by:

$$R_M(n) = \prod_K e^{-f_K t_K} \left[\sum_{j=0}^{n_K} e^{-m_K f_K t_K} \frac{(m_K f_K t_K)^j}{j!} \right]^{n(K)} \qquad (1)$$

where n is the total number of spares allocated, n_K is the number of spares allocated to the modules of the K^{th} supermodule, and

$$n = \sum_K n_K \; n(K).$$

[redacted]

$$R_M(n) = R_M(n-1) \max_K \left[\frac{\displaystyle\sum_{j=o}^{n_k+1} e^{-m_K f_K t_K} \frac{(m_K f_K t_K)^j}{j!}}{\displaystyle\sum_{j=o}^{n_K} e^{-m_K f_K t_K} \frac{(m_K f_K t_K)^j}{j!}} \right] \tag{2}$$

determines the graph of reliability versus number of spares.

The weight as a function of spares is given by:

$$W(n) = \sum_{K=1}^{K} n_K \; n(K) \; W_K \; + W_o , \tag{3}$$

where W_o is the initial weight and W_K is the weight per spare for the K^{th} module.

The reliability for the automatic maintenance mode is given by:

$$R_A(n) = \prod_K e^{-f_K t_K} \; (1 + F_K t_K)^{n_K \; n(K)} \tag{4}$$

c. Analysis applied to Apollo subsystems

An analysis based on Model 5 was applied to the Apollo guidance and communications subsystems. Only the electronics portion of the guidance subsystem was considered and only the electronics of the deep space communications and telemetry portions of the communications subsystem were considered for maintenance (See Table 1-12). The results of these analyses are presented in Tables 1-13 (guidance) and 14 (deep space communications), and in Fig. 1-II-3 (guidance) and 1-II-4 (deep space communications). It should be pointed out that spares are allocated for manned maintenance to maximize reliability per unit weight, and the same spares are allocated for automatic maintenance according to Maintenance Class IV. This does not necessarily maximize reliability per unit weight for the automatic maintenance system. That is, there might be some better way of utilizing the same weight by a different allocation of spares to a different supermodule. However, Model 5 shows that, for the same weight of spares, manned maintenance (systems backup) is always

[redacted]

TABLE 1-12

Assumptions about the Guidance and Deep Space Communications Subsystem

Guidance subsystem (electronic spares only)

W_0 = 42 pounds K = 3

Astro-inertial platform	Astro-inertial tracker	Guidance digital computer
F_1 = 0.000197	F_2 = .000066	F_3 = 0.003970
t_1 = 2,000	t_2 = 200	t_3 = 200
N_1 = 12	N_2 = 9	N_3 = 40
n(1) = 4	n(2) = 3	n(3) = 10
m_1 = 3	m_2 = 3	m_3 = 4
f_1 = 0.000016	f_2 = 0.00000073	f_3 = 0.0000993
w_1 = 0.25 lb	w_2 = 0.25 lb	w_3 = 2.25 lb
$W0_1$ = 12 lb	$W0_2$ = 10 lb	$W0_3$ = 20 lb

Deep Space Communications subsystem (electronic spares only)

W_0 = 68 pounds K = 5

PCM & PDM systems	On-board tape recorder	DSIF transmitter	DSIF receiver	S-band beacon
F_1 = 0.001646	F_2 = 0.000042	F_3 0.000399	F_4 = 0.000154	F_5 = 0.001934
t_1 = 336	t_2 = 336	t_3 = 336	t_4 = 336	t_5 = 336
N_1 = 60	N_2 = 14	N_3 = 1	N_4 = 1	N_5 = 20
n(1) = 10	n(2) = 7	n(3) = 1	n(4) = 1	n(5) = 10
m_1 = 6	m_2 = 2	m_3 = 1	m_4 = 1	m_5 = 2
f_1 = 0.0002743	f_2 = 0.000003	f_3 = .000399	f_4 = 0.000154	f_5 = 0.0000967
w_1 = 0.25 lb	w_2 = 0.25 lb	w_3 = 4 lb	w_4 = 1 lb	w_5 = 0.25 lb
W_1 = 2.25 lb	W_2 = 1.75 lb	W_3 = 4 lb	W_4 = 1 lb	W_5 = 2.50 lb
$W0_1$ = 40 lb	$W0_2$ = 9 lb	$W0_3$ = 4 lb	$W0_4$ = 1 lb	$W0_5$ = 14 lb

TABLE 1-13

Results of the Weight versus Reliability Analysis of Guidance Subsystem with Manned or Automatic Electronics Maintenance

CUMULATIVE WEIGHT (lb)	RELIABILITY Manned Maintenance	RELIABILITY Automatic Maintenance
42.00	0.301	0.301
44.50	0.645	0.366
45.50	0.939	0.408
48.00	0.967	0.496
49.00	0.984	0.533
49.75	0.996	0.555
52.25	0.997	0.676
53.25	0.997	0.680

TABLE 1-14

Results of the Weight versus Reliability Analysis of Deep Space Communications and Telemetry with Manned or Automatic Electronics Maintenance

CUMULATIVE WEIGHT (lb)	RELIABILITY Manned Maintenance	RELIABILITY Automatic Maintenance
68.0	0.246	0.246
70.5	0.470	0.340
73.0	0.812	0.373
77.0	0.918	0.422
78.0	0.964	0.442
80.5	0.983	0.609
83.0	0.993	0.668
92.0	0.999	0.675

superior to automatic maintenance (modular backup). If maintenance is not considered and redundant equipment is added to improve reliability, the picture presented by Figs. 1-II-3 and 1-II-4 are even more favorable to manned maintenance. This is because electronic modules are very light when compared to the overall weight of the component, and yet they represent a major source of unreliability. The analyses, which are admittedly very crude, can be improved in accuracy as more data about components and modules becomes available.

3. Power analyses

It has been suggested that the crew of a space craft could be used as energy source, to provide electrical or mechanical energy. There are two principal reasons advanced for this suggestion:

(1) Man has a significant energy capability.

(2) It may be necessary for the crew to exercise to avoid the deleterious effects of prolonged weightlessness on muscle tonus. This energy should not be wasted.

Krendel (Ref. 3) has reviewed the existing data on the mechanical power output of men, and has suggested a scheme for designing manpowered devices for optimal power transfer from man to machine. From this work it is possible to estimate the available energy of man. Fig. 1-II-5 summarizes the energy man can contribute to a system when given a set of equipment for such purposes. In brief, he can continuously produce 0.13 horsepower or 97 watts. With an eight-hour work day a man could produce about 800 watt-hours per day. Fig. 1-II-5 also indicates the potential energy output for shorter periods of time. Fig. 1-II-6 shows the additional energy output to be gained from extra equipment and men. This energy is available for several purposes such as mechanical actuation or electrical power supply.

A study has also been made of the use of manpower for electrical energy. The Apollo electric power subsystem provides approximately 1800 watts. One man can supply approximately 100 watts per hour for eight hours. This source of power would be most valuable during the recovery period where 100 watts are required for 72 hours. To accomplish this each man would have to be sound and healthy following the landing, and the men would have to spell each other for round-the-clock operation. This level of energy expenditure would increase the food, water and oxygen requirements and place an increased demand on the environmental control system for removal of carbon dioxide, water vapor and heat. This increased demand on the environmental control system also means increased electrical power requirements. If the crew were provided with the appropriate equipment they could serve as a significant additional source of power in the event of an emergency.

SUMMARY

We have in the preceding pages shown the functions and role man will have in the system. We have also, as a result of our analyses, shown that the crew contributes to the system:

(1) By increasing the reliability of the system.

(2) By decreasing the weight for subsystems when acting as a maintenance source.

(3) By increasing the effectiveness of the system as it performs its mission because of the in-flight systems checkout procedure.

(4) By acting as a possible source of emergency power.

We will in the rest of the report discuss the contribution of man to the system controlling the vehicle during re-entry and landing.

REFERENCES

1. Grodsky, M. A., and Sorkin, R. D., "Man's Contribution to an Operational Space Station Concept," Paper presented at the First National Symposium on Manned Space Stations, April 1960, Los Angeles, California

2. Grodsky, M. A., and Levy, G. W., "Human Maintenance Functions in Man-Machine Systems," Paper presented at the West Coast Electronic Convention, IRE, August 1960, San Diego, California

3. Krendel, E. S., "The Mechanical Power Output of Men," Franklin Institute Report, F-A1982 January 1958

III. SPACECRAFT DISPLAYS AND ARRANGEMENT

We have discussed in great detail the functions of the crew within the Apollo system. In order to ensure high crew performance consideration must be given to the spacecraft arrangement, the displays for the crew and the modes of vehicular control. Also to be considered, are crew furnishings. This chapter will present each of these areas in detail.

A. SPACECRAFT DESIGN

1. Configuration

By reference to Fig. 1-III-A an overall idea of the main lines can be gained. The spacecraft is composed basically of a command module, a mission module and a propulsion module. There are the following additional features:

The abort module consists of a multiple nozzle, truss-mounted rocket which is carried ahead of the re-entry vehicle (command module).

The re-entry vehicle contains provisions for three crew stations, as well as the equipment required for abort, re-entry and landing and survival after landing. One crew station is a primary duty station to be manned at all times. The other stations are minimal and provide redundancy and crew safety. The crew is restricted to the re-entry vehicle during the launch and re-entry phases of all flights.

Access to the mission module is provided by a connecting tunnel.

The mission module contains or supports all equipments except those described for the re-entry vehicle. In addition, sanitary facilities, food facilities and provisions for a primary scientific duty station are made.

The landing operation is to consist of a parachute descent followed by a final deceleration to touch-down speed. This is provided by a retrorocket.

2. Command Module

The command module may be subdivided into external structure, internal structure, recovery gear, surface controls, reaction controls, instruments, guidance, communication, telemetry, instrumentation, power systems, furnishings or equipment and environmental control for both personnel, equipment and structure.

The external structure is considered to include the external heat shield, the pressure shell and structural cooling water required during re-entry.

The internal structure includes frames, posts, beams, flooring and provisions attached to basic structures for equipment, seats, consoles and so forth.

The recovery gear consists of an 11-foot diameter FIST ribbon drogue parachute, then an 81-foot Glidesail parachute. These are provided with complete backup. For touchdown, a single retrorocket is provided to reduce both vertical and horizontal velocity to zero.

Surface control flaps are actuated by a hot gas generator acting on a motor the output shaft of which drives a belt attached to a push rod on the flap.

Reaction controls are provided for both the command and mission modules. Since the mission module controls are used for the space craft injection and midcourse attitude control, the command module contains only those reaction jets needed for re-entry and emergency use.

Power for the command and mission modules is provided by fuel cells whose by-product of water supplies the crew.

There are three types of guidance utilized in the Apollo vehicle:

(1) The automatic guidance system consists of an inertial platform, astrotracker, and computer.

(2) The manual guidance system consists of a telesextant, miniature inertial platform, CRT, and utilizes the computer from the automatic system.

(3) The ground guidance system supplements on-board guidance by the astronaut manually feeding the computer.

Instruments include velocity, altitude, attitude, accelerometer, back-up gyro, position and course, cabin pressure, suit pressure, structural temperature, periscope, control position, oxygen pressure, N_2 pressure, sequencer, warning lights and more which are discussed further later in this section.

Instrumentation includes cameras, vehicle telemetry data, scientific telemetry data, X-Band telemetry, and tape recorders.

The communications system includes:

(1) Voice communication--HF radio, UHF radio.

(2) Command receivers--UHF, HF, X-Band and decoders.

(3) Recovery communications-- HF, UHF, beacons, batteries, lights, dye markers, radar chaff and antennas.

The furnishings and equipment include three seats, panels and consoles, cockpit trim and insulation, survival kits, food, water (emergency), containers, and waste disposal units.

The environmental control system includes the heat exchanger, pumps, water glycol tanks, storage, manifolds and plumbing.

The command module (see Fig. 1-III-2) contains the astronauts and equipments necessary for controlling the spacecraft during orbit, injection, ejection and re-entry-recovery.

The following sections discuss in detail the information requirements for control of the vehicle, the division of duties for the crew, the information requirements for successful flight of the vehicle and a discussion of panel arrangement and crew stations.

The display arrangement will be discussed in detail later in this Chapter.

The seating and lighting will be discussed here for the command module.

Figure 1-III-3 illustrates the seats in the command module. The seat was designed to protect the crew member from the forces of acceleration and deceleration as well as provide him with a comfortable position from which to work.

The total seat structure (the forward seats are oppositely pivoted) pivots on an axis (Fig. 1-III-3) off-center of the crew member's forward axis to permit ease of entrance to and exit from the work position. Because the Engineer-Scientist's seat is on the rear bulkhead, it is not necessary for it to pivot. All seats tilt forward (as in Fig. 1-III-3, c) 10 degrees for launch from the nominal position. The nominal position, all the way to the rear, is the re-entry position. The restraint straps and connections are directly affixed to the seat structure and in no way affect seat movement.

The seat is adjustable for height from the floors and the back is adjustable for tilt to suit each individual. The forward-backward tilt and up-down travel are developed by electric jacks under the direct control of the individual.

Arm rests are provided which contain the control sticks. However, any individual's bucket portion of the seat may be installed with ease and does not degrade the performance of the seat. The buckets are equally comfortable for the suited and unsuited condition.

The seat is mounted on a piston (Fig. 1-III-3, b and c) and further restrained by the bushing fixture at the seat's head. On landing the total seat moves downward and the piston crushes applicable material located in the piston well (Fig. 1-III-3, b and c). The Engineer-Scientist's seat operates exactly the same but is restrained by its connection via a track and rollers system to the rear bulkhead.

The bucket portion protects the complete body (head, trunk, and legs) from rearward body movement. The bucket also allows the legs to flex on landing. Also contained within each seat is an emergency sanitation facility. The displays and controls within the command module are discussed in another section of this report.

3. Mission Module

The mission module may be subdivided into module structure, furnishings and equipment, environmental controls, reaction controls, electronic and instrumentation equipment, power systems and separation devices.

The external structure of the module contains the pressure shell supporting longeron module separation system. The door or hatch way for main crew entrance is positioned in the external shell (see Figs. 1-III-4 and 5). Also positioned in the outer shell (interface of the command and mission module) is the hatchway to the command module.

The internal structure contains flooring, supports and structures necessary to support and mount all internal furnishings and equipment.

The mission module contains most of the supplies of oxygen, nitrogen and filtering equipment; approximately half of the cooling system components and a small part of the heat sink system. The command module supplies are replenished automatically by those in the mission module as needed until reentry (module separation).

The mission module contains the reaction controls used in spacecraft injection and midcourse attitude control. It also contains one of the fuel cells.

Within the electrical control system the mission module contains the electrical distribution racks and control panel.

Communication equipment contained in the mission includes the UHF receivers and transmitters, antenna multiplexers, S-Band transmitters and receivers, S-Band tracking beacon and C-beacon.

Instrumentation equipment includes a tape recorder, lunar camera, scientific equipment racks and console, signal conditioning package, radiation detectors, micrometeorite detectors, and solar flare detectors.

Furnishings and related equipment include the sanitation facility (seat), potable water tanks, food and galley facility, waste storage cabinets and associated racks.

Environmental controls include the water recovery system and storage tanks, heat exchanger and fan system.

Propulsion items include the main engine, propellant tanks, vernier engine, vernier propellant tanks and helium tanks.

In the mission module arrangement a scientific duty station, appropriately designed for a particular mission, can be installed as a partially prefabricated unit. In addition, sanitation facilities and life support equipments are planned as a fixed part of the module.

When mission duration is sufficient to make equipment maintenance and/or repair a necessity, this facility must also be located in the mission module.

Consideration of eventual use on the lunar surface suggests the orientation shown for this module. Since gravitational effects will be encountered there, it will be necessary to make "normal" direction supports for crew and equipment. This is no penalty to the vehicle, since the launching accelerations are also in this direction and are much larger in magnitude.

a. Configuration and workplace layout

The mission module is cylindrical in shape with domes on either end. Entrance to the spacecraft while on the launch pad is through a 36-inch hatch in one of these domes that is sealed after crew installation. Entrance to the command module is gained through a 36-inch tubular passage in the top of the mission module using steps provided on the racks beneath the passage (see Fig. 1-III-5).

The working area within the module is 9 feet long, 38 inches wide and 75 inches high (decreasing to 68 inches on the ends).

Most of the astronaut activity in the mission module will be conducted while seated on the feces collection unit restrained by straps since he will only be in this module during weightless stages of the trip. From this position the astronaut can use the galley, camera, scientific equipment, and, of course the sanitation facilities, as can be seen in Fig. 1-III-5. All these facilities are within his reach while seated on the unit. To accommodate the astronaut further, the feces collection unit will be track-mounted to allow better positioning for long term tasks. The astronaut has access to the environmental control unit and electrical racks at the opposite end of the module if and when he needs access for maintenance on extended flights.

The remainder of this section will describe in very limited detail the mission module main task equipments.

b. Scientific station

There are an unending number of scientific missions conceivable for the Apollo spacecraft. These are a few examples:

[redacted]

(1) Measurements from an orbit of the moon of its gravitational fields.

(2) Measurement of the moon's thermal balance.

(3) Spectrometer measurements of the moon's atmospheric composition and density.

(4) Radiation measurements in deep space.

(5) Spectrometer measurements of the moon's crust composition and density.

(6) Survey of the moon's crust after lunar landing.

Of necessity, various equipments will be needed for even the few examples mentioned. Within the initial design of the vehicle both space and weight will be allowed for anticipated equipments. Their location is noted in Figs. 1-III-4 and 5.

c. Sanitation facilities

Feces collection unit. Figure 1-III-6 illustrates the recommended AMF waste collection unit. To operate, the man straps himself to the seat centering his anus over the form-fitting ring. The center drawer (Fig. 1-III-7) is then moved forward and a disposable feces bag unrolled and inserted through the form, with the top stretched over the form and bottom pulled down into the retaining clip. The drawer is then returned under the seat so that the snap-on connector engages a vacuum line. During defecation the man operates the flush lever to throttle the flow of cabin gas (1) through a sponge lining between the bag and anus, (2) through the bag to drag feces downward, (3) through a sponge in the bottom of the bag and (4) out to space through the throttle valve. After defecation, the man increases the flush rate, operates the pinchers which causes the feces to be trapped in the bottom of the bag. He then wipes himself, stuffs the paper in the open top of the bag, moves the drawer forward (which closes the vacuum line), opens the pinchers, removes the bag (thus allowing the top to contract and have the paper serve as a closure) and puts it into storage.

Urine collection unit. Figure 1-III-7 illustrates how the center drawer can accommodate the portable urine collection unit developed by AMF. To operate, the bottle under the bellows is squeezed to collapse the bellows and the penis inserted into the tulip-shaped receptacle. During micturition the crew member pushes the spool valve on the front of the unit open and allows the bellows to expand at a rate sufficient to provide a slight suction on the penis. When micturition is completed and the bottle fully expanded, the spool valve is pushed to the closed position to close off the bottle and vent the penis receptacle. The urine can then be transported to the water recovery system, and directly transferred into the contaminated water storage. After emptying, a

[redacted]

disinfectant should be placed into the bottle to minimize bacteria growth upon refilling. When not being used, the bellows is pushed down and the cover kept closed.

The feces and urine collection unit* enables the man to perform defecation and urination comfortably although not simultaneously. The seat of the unit is approximately 15 inches from the floor which is adequate for support and to enable him when seated to place his feet in the thrust toe holds provided. The seat itself is shaped to support the suited body as well as the unsuited body. The backrest of the unit is also shaped to the body and has side braces to prevent the buttocks and thighs from horizontal motion.

The feces and urination collection unit assembly pulls out from under the seat section when needed. At all other times the unit is retracted and the sanitation unit serves very adequately as a seat from which the crew member can operate the mission module controls.

The sanitation facility also includes the hygienic station which is the storage and disposal cabinet for the prewetted sponges.

Vomit receptacle. In the event that a crew member experiences incoercible vomiting, the regurgitated matter can simply be collected in a bag fabricated from a plastic which is permeable to gas, but will retain liquids and solids. Such a bag would enable the crew member to tightly seal the neck of the bag to his face around the mouth, and yet allow expelled gases to permeate the bag, thus preventing pressure buildup in the bag. The AMF teflon-coated fabric, with controlled pore sizes, could be used for this application.

Waste stowage facility. Waste will be stowed in a plastic bag with chemical agents in a refrigeration locker next to the environmental control system.

d. Galley facilities

For the initial flights, foods will be simple, needing no cooking or refrigeration. More detail can be gained from Chapter III of this report. The galley facility is located directly in front of the crew member (see Fig. 1-III-4).

e. Camera

The camera will be mounted external to the mission module with internal access to the film packs. A two-degree gimballed mirror will be used to allow image movement. Controls for the mirror will be internally mounted. There is a locker for film stowage close to the camera controls.

* Study done by the American Machine and Foundry Company for The Martin Company.

f. Movement of astronaut

Some form of contact adhesive between the astronaut and his walkways will be provided. The astronaut's shoes, the floors, the seat of his pants and any chair should contain some form of contact adhesive to assist him in moving about in weightlessness.

B. DETERMINATION OF INFORMATION REQUIREMENTS

An important consideration in the design of a manned vehicle is the presentation and use of displayed information. Since man's performance outputs within the Apollo system are to some extent dependent on the information presented to him, the integration of displays and controls was emphasized. Of particular importance are the type and number of displays, the method of display system integration and the operator stations. However, in order to consider the display and control system, delineation of the information requirements for the various mission phases was necessary.

The initial step in determining the information requirements was the study of mission objectives, probable equipment and probable procedures. The next step was the development of a task analysis to provide a systematic method for studying the entire mission both from an overall viewpoint and in detail. The task analysis as stated earlier details the time line progression of the mission, the operator's objectives, possible actions, and briefly, information requirements. The information requirements for each operational phase are classified as to accuracy and range.

The task analysis was reviewed and summarized into Tables 1-15, 1-16 and 1-17. Table 1-15 "Operator Information Requirements", delineates the detailed information requirements for the various mission phases and groups the information into related categories which can be instrumented and displayed. This tabulation is necessary for developing the preliminary layout or "model" for the display system and will also serve as a guide for instrumentation development. Tables 1-16 and 1-17, "Operator Display Requirements" and "Operator Control Requirements" summarize the display and control requirements of the vehicle.

Tables 1-16 and 1-17 furnish the necessary material to transform the information requirements into display and control form and allow the establishment of operator stations. Thus, the task analysis and the resulting information and control requirements provide a starting point for the specification of operator stations, operator tasks, displays and controls, as well as needed automation.

[redacted]

TABLE 1-15

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
1. VEHICLE ATTITUDE ANGLES					Provide indication of automatic system even when operator is not controlling
1.A Earth Reference				Monitor trajectory	
1.A.1 Roll	Launch thru injection	$\pm 180°$	$\pm 1°$	Roll to heading in 1st stage	
				Aerodynamic control Lateral axis	Scheduled turn
	Re-entry	$\pm 90°$	$\pm 1°$		
1.A.2 Yaw	Launch-coast	$\pm 90°$	$\pm 1°$	Monitor trajectory	
	Re-entry	$\pm 30°$	$\pm 1°$	Lateral axis control	
	Injection	$\pm 2°$	$\pm 0.1°$	Injection accuracy	
1.A.3 Pitch	Launch-coast	$+90$ to $0°$	$\pm 1/2°$	Monitor trajectory as per schedule	
	Injection	$\pm 2°$	$\pm 0.1°$	Injection accuracy	
	Re-entry	$\pm 60°$	$\pm 1/2°$	Transfer to aerodynamic flight, transient control between holding angle of attack, g, or heating	

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
1.B Propulsion Direction Reference					
1.B.1 Roll	Vernier midcourse injections	±360°	None	Simplify control problem by having roll axis out of problem	Orient vehicle so that thrust is along roll axis of rotation
1.B.2 Yaw 1.B.3 Pitch	Vernier midcourse injections	±10°	±0.1°	Hold vehicle to a null attitude Correction is being properly controlled	Allows navigation correction independent of prime reference system
1.C Lunar Reference					Reference to moon vertical and location postulated necessary
1.C.1 Roll 1.C.2 Yaw 1.C.3 Pitch	Lunar orbit	±360°	±1°	Control vehicle Control area viewed by various equipment Optical navigational fix Enable observation via window, periscope or kinescope	Photography: scientific equipment, i.e., EM, infra-red, radiation, etc.

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
1.D Orbit Reference					Assume sun-oriented vehicle with roll axis pointed along direction to sun (Allows 1 axis maneuvers)
1.D.1 Roll	Orbit phases	$\pm 360°$	$\pm 3°$	Observation	
				Maintain orientation	Antenna direction
				Cooling radiation areas properly oriented	
	Star or planet tracking	$\pm 360°$		Provide reference for and measurement of position	
1.D.2 Yaw, 1.D.3 Pitch	Orbit phases	$\pm 360°$	$\pm 3°$	Observation	
				Maintain orientation of vehicle toward sun	
				Stable system for antenna	
	Star or planet tracking	$\pm 360°$	Minimum error	Provide reference for and measurement of position	

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
2. ACCELERATION	Launch	0-4.5 g	±0.1 g	Monitor propulsion performance of booster	Tangential acceleration Other accelerations are obtained by inertial guidance system but are not thought useable by man
				Note ignitions and cutoffs	
				Help in abort decisions	
	Midcourse vernier Corrections	0-0.1 g	±0.05 g	Note propulsion on	
	Lunar injection and ejection	0-1.0 g	±0.1 g	Monitor propulsion	
	Re-entry	0-0.1 g	±0.05 g	Atmosphere has been re-entered	
		0-10 g	±0.1 g	Fly g schedule	Re-entry technique still to be formulated
				Prevent over-stress on men and equipment	
				Prevent over-heating	
3. PRESSURE ALTITUDE	Launch	0-110,000 ft.	±2%	Rough check on trajectory	Initial accuracy greater than +2000 feet

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
				Cross-check operation of inertial system	
				Check for pressure alt. actuated seq-uences	
				Check environ-mental pressure control system	(Value of rate of climb should be considered)
	Re-entry	110,000 ft	$\pm$2000 ft	Indicate end of re-entry phase	
	Landing	80,000 ft 15,000 ft	$\pm$1000 ft $\pm$1000 ft	Drogue chute deploy Main chute deploy	Backup altitude sensors or change deployment procedure
4. DYNAMIC PRESSURE "q"	Launch	0-600 psf	$\pm$5%	Type of abort Trajectory check	Mercury did not use "q" meter due to preplanned nature of aborts. This may not be the case here
	Re-entry	0-650 psf	$\pm$5%	Re-entry schedule Type of control Reaction-aero-dynamic Relationship to heating Chute deployment	Indicated airspeed or Mach meter might be used instead of "q"

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
5. ANGLE OF ATTACK	Launch		±1/4°	Missiles avoid lift on launch Indication of trajectory	
	Re-entry	+60°	±1/4°	Control parameter in re-entry corridor Control system or manual flight will probably use fixed value for parts of aerodynamic flight Related to flight path in aerodynamic flight Stability and maneuver indicator Closely related to heating	Used in X-15 and Dyna-Soar re-entry control Used to establish zero lift trajectory Used in re-entry to point of g buildup
6. VEHICLE ANGULAR RATES	Separation from Saturn booster	±10°/sec	±0.1°/sec	Recovery from tumbling	Mercury indicator ±6°/sec may need larger scale
{Roll Yaw Pitch}	Vernier, midcourse correction, injection and ejection in lunar orbit	±10°/sec	±0.1°/sec	Prime manual control of space vehicle during propulsion activity	Space vehicle - inertial body without damping

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
	Separation of mission module	$\pm 10°$/sec	$\pm 0.1\pm$/sec	Recovery from tumbling	
	Initial re-entry	$\pm 10°$/sec	$\pm 0.1°$/sec	Provide initial damping on re-entry	Stabilize vehicle. Mercury uses rate damper only in this mode
7. SIDE-SLIP INDICATION	Launch		$\pm 1/4°$	Trajectory indication should be zero	Need for this indication needs further study
	Re-entry	$\pm 15°$	$\pm 1/4°$	Stability criteria maneuver limit Check on autopilot co-ordination	
8. FLIGHT PATH ANGLE	Launch	$\pm 90°$	$\pm 1/4°$	Prime scheduled trajectory monitor	Used presently in re-entry computations and instrumentation.
	Re-entry	$\pm 10°$	$\pm 1/4°$	Re-entry corridor described in terms of flight path Difficulty of re-entry is established from approach to limits	Dyna-Soar displays this Inertial value
9. SKIN TEMPERATURE	Re-entry	0-3200°F		Re-entry technique	Instrumentation development needed

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
				Limiting parameter on structure	Time dependent limit
				Energy dissipation --related to altitude (potential) velocity (kinetic) energy	Several key points on vehicle should be indicated Heating rate may be an important display
10. INERTIAL ALTITUDE	Launch	0-1,120,000 ft	±1000 ft	Monitor trajectory	
				Check inertial system against pressure altitude	
				Tower separation	
	Coast	975,000-340,000 ft	±10,000 ft	Monitor trajectory and prepare for injection	
	Injection	340,000-400,000 ft	±10,000 ft	Monitor trajectory	
	Trajectory (range to earth)	Orbit		Means of checking and fixing inertial information	Change in reference to distance to earth, same measure radar ranging would give
	Re-entry	400,000-100,000 ft	±1000 ft	Entry to corridor	
				Potential energy of vehicle	

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
				Approach of aero-dynamic condition Check on time sequencing	
11. INERTIAL VELOCITY	Launch 1st stage	0-4256 fps	±50 fps	Monitor propulsion	Derived from inertial system
	2nd stage	4256-15,800 fps	±50 fps	Monitor inertial system	
	3rd stage	15,800-25,000 fps	±50 fps	Monitor trajectory	
	Coast	25,500-26,500 fps	±50 fps		
	Injection to lunar trajectory	26,500-36,100 fps	±25 fps	Indicate injection accuracy	
	Vernier and midcourse corrections	±25 fps	±1 fps	Indicate correction quality	
	Inject to and from lunar orbit	6530-3800 fps and back to 6530 fps	±25 fps	Lunar orbit decision and success of injection	
	Re-entry	35,000 fps to Mach 1.5 at 100,000 ft	±1000 fps	Kinetic energy Re-entry schedule Time to go	

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
12. COURSE MADE GOOD	Re-entry control	Maneuver limits	$\pm 0.5°$	Prediction of touch-down point by track along ground Check on inertial equipment Prediction of re-entry initial conditions	Will be part of navigational planning Inertial information
13. VISUAL VIEW OF EXTERIOR					
Earth, Moon	Trans-lunar trajectory			Obtain navigational fix Note attitude orientation of vehicle	Attitude is cross checked on inertial system
Stars				Check star tracker acquisition Aid star tracker acquisition	
Moon	Lunar injection			Visual orientation to moon may provide most accurate fix--Analysis shows that if salient feature on the moon can be tracked, fix can be correct to within a few feet	Use particular crater or other land mark Need exists for accurate navigation fix at moon--where earth information is faulty or non-existent

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
	Lunar orbit			Attitude reference	Use in same way as in Mercury
				Distance to moon	
	Re-entry			Means of relating to earth's vertical reference system	(Secondary system)
	Landing			Control of parachute system for landing point	Control drift upon impact (0-30 knots)
				Means of observing chute deployment	
14. RADAR--RADIO RANGE AND ANGLE TO EARTH	All trajectory computations			Means of determining position in trajectory All navigational decisions can be checked	
				Means of checking inertial guidance package	
				Means of fixing inertial guidance system	
				Means of training radio antenna	

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
15. SITUATION WITH RESPECT TO NOMINAL TRAJECTORY $r \begin{cases} \Delta X \\ \Delta Y \\ \Delta Z \end{cases}$ $r \begin{cases} \Delta \dot{X} \\ \Delta \dot{Y} \\ \Delta \dot{Z} \end{cases}$	Trajectory			Determine quality of trajectory Determine need for correction or abort or new nominal Initial conditions for computation of corrections Monitor on quality of inertial system	Situation with respect to space would not yield useful data General map plot sufficient Decision for man which is most important Error may be due to either (a) real error (b) measurement error
16. INITIAL RANGE AND ANGLE TO EARTH	All trajectory computations			Prime reference to radio-radar derived information Quality of inertial guidance information	
17. TRAJECTORY MODIFICATION DATA a. Attitude orientation b. Schedule 1) When 2) Coast time 3) Duration 4) Thrust level	Propulsion expenditures			Visual reading of manual inputs Readout of computer correction Means of checking trial solution	May use computer input-output readout

[redacted]

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
18. LANDING MANEUVER DISPLAY	Re-entry			Possible landing area with respect to vehicle performance capability and energy of vehicle	
				Allows for planning in energy management	Choice (if any) of tactic
				Prediction of landing (if any) under present conditions	Consequence of possible tactic
19. POSITION (LONGITUDE AND LATITUDE) WITH RESPECT TO EARTH	Launch 3rd stage	315-1630 miles	± 25 miles	Monitor trajectory	Contact and observation by earth important during launch
	Coast	1630-3730 miles		Note communication link to earth	Map display of inertial information
	Injection	3730-4700 miles			Map or overlay information may be enough
	Re-entry		± 10 miles	Land at desired location	
				Plan re-entry	
				Compare possible maneuver area of display to possible landing sites	

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
20. LUNAR POSITION AND MAP DETAIL	Lunar orbit			Control of orbit about moon Anticipation of injection to earth Scientific information Control of observation equipment in relation to moon geography Lunar fix data	Will navigation system switch to lunar coordinates? Will map be enough? May be part of general horizontal display
21. STAR TRACKER INFORMATION Azimuth Train Elevation	Orbit determination in navigational fix			Does inertial system know where stars are? Is fix information being obtained from proper star? Provide manual method of navigational fix, general location of star Correction (midcourse) could be oriented manually to a particular star	Platform orientation and correction Will tracker be fixed or gimballed? 4 sec limit on tracker? 20 sec Man is of use in selecting and acquiring star Use cageable gyro system for short term stability
22. FLAP POSITION INDICATORS	Re-entry landing		$\pm 2°$	Surface trim on reentry Surfaces are controlled	

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
				Surfaces trimmed to streamline (landing)	
23. COMPUTER INPUT-OUTPUT READOUT	All navigation phases			Provide periodic readout of system performance Check on all operator input-output to computer Allow readout of items not warranting continuous readout Troubleshooting Check on content of computer memory	
24. TIME AND SEQUENCE INDICATOR	All phases			Times to important events must be known to allow for preparation Man will backup crucial functions with redundant controls Indication of success and status of events must be known Timer (stop watch for various navigation and miscellaneous functions must be provided	 Staging tower separation, capsule separations

[redacted]

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
25. SYSTEM CONDITION	All phases		Go-No-Go	General status of equipment Warning of danger	Classification of information needed as to importance and action time Indications of dangerous condition probably need repeating at all duty stations
26. MAIN PROPULSION SYSTEM					
A. Oxygen					
A.1 Pressure	Injection into lunar orbit and ejection from lunar orbit	0-30 psi	±1 psi	Monitor oxygen supply pressure	
A.2 Temperature		-297°F±20°	±5°	Monitor temperature of oxygen supply	
A.3 Quantity		0-100%	±2%	Indicate O_2 remaining	
B. Hydrogen					
B.1 Pressure		0-30 psi	±1 psi	Monitor H_2 supply pressure	
B.2 Temperature		-423°F±20°	±5°	Monitor H_2 supply temperature	

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
B.3 Quantity		0-100%	±2%	Indicate H_2 remaining	
C. Valve Pressure		500-4500 psi	±50 psi	Monitors pressure on O_2 and H_2 in tanks	
D. Solenoid Temperature		-100°F-+100°F	±10°	Monitors temperature of valve solenoid	
E. Chamber Pressure				Monitors pressure in combustion chamber	
27. ATTITUDE PROPULSION SYSTEM					
A. Propellant Temperature					
A.1 Oxidizer	Injection to re-entry	+10-+70°F	±5°	Monitors oxidizer temperature	
A.2 Fuel	Injection to re-entry	+20-+70°F	±5°	Monitors fuel temperature	
B. Supply Pressure	Injection to re-entry	500-4500 psi	±50 psi	Monitors pressure in fuel and oxidizer tanks	
C. Total Pounds Remaining	Injection to re-entry	0 - X0 lb	±1 lb	Monitors amount of fuel and oxidizer left	

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
D. Total On Time Remaining	Injection to re-entry	0-99 min 59 sec	±1 min	Indicates "on" time of attitude rockets	
28. ELECTRIC POWER					
A. Volts					
A.1 Fuel Cells 1-3	Launch to re-entry				
A.2 Battery	Re-entry to landing and recovery				Used in emergency conditions
A.3 CM ESS Bus	Launch to re-entry	28 VDC	±1 V		
A.4 MM ESS Bus	Re-entry to recovery	28 VDC	±1 V		
A.5 Recovery Bus	Re-entry to recovery	28 VDC			
B. Amperes					
B.1 Fuel cells 1-3	Launch to landing re-entry				
29. CLOCK	Launch to recovery	336 hrs	±1 sec		
30. RADIATION	3rd stage to re-entry			Measure total radiation accumulated	5 rem max:
31. FLAP POWER					
A. Fuel Pressure Re-entry				Monitors fuel pressure for flap system	

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
B. System Temperature				Measures gas temperature for flap system	
C. System Pressure	Re-entry			Measures hot gas pressure for flap actuation	
32. CABIN PRESSURE					
A. Command	Launch to landing	5-12 psi	±1 psi		
B. Mission	Launch to re-entry	5-12 psi	±1 psi		
33. CABIN TEMPERATURE					
A. Command	Launch to landing	70°F	±10°		
B. Mission	Launch to re-entry	70°F	±10°		
34. CABIN RELATIVE HUMIDITY					
A. Command	Launch to landing	0-100%	±10%	Indicates system malfunction	
35. FLIGHT SUITS					
A. Pressure	Launch to landing	5 psi		Monitor for leaks	
B. CO_2 PP					
C. O_2 PP					

TABLE 1-15 (cont)

Summary of Operator Information Requirements

Parameter	Operational Phase	Range	Accuracy	Why Needed	Notes
36. AIR SUPPLY					
A. Normal O_2(2)	Launch to landing			Crew safety	
B. Emerg. O_2	Launch to landing			Crew safety	
C. N_2	Launch to landing			Crew safety	
37. PARTIAL PRESSURE					
A. Oxygen	Launch to landing			Monitor crew safety	
B. CO_2	Launch to landing			Monitor crew safety	
38. CABIN COOLING SYSTEM					
A. Pressure	Launch to landing			Monitor operation	
B. Temperature	Launch to landing			Monitor operation	

TABLE 1-16

Operator Display Requirements

System	Part	Type of Display
Environment Warning	Command Module <u>and</u> Mission Module	
	Press 12	
	Press 5	
	CO_2 partial pressure (2)	Message lights
	O_2 partial pressure (2)	Message lights
	Relative humidity	Message lights
	Temperature	Message lights
	O_2 quantity (2)	Message lights
	O_2 emergency	Message lights
	N_2 quantity	Message lights
	Suits	
	CO_2 partial pressure (3)	Message lights
	O_2 partial pressure (3)	Message lights
	Pressure (Total) (3)	Message lights
	Hold 1	Info switch button
	Hold 2	Info switch button
	Hold 3	Info switch button
Ten-inch Scope Display (2)	Diversified information display	10-inch kinescope
Scope Control Panel	No. 1 computer printer (2)	Info switch button
	No. 2 computer printer (2)	Info switch button
	Landing track generator (2)	Info switch button
	Course error pattern (2)	Info switch button
	Periscope camera (2)	Info switch button
	Printer recall (2)	Info switch button
Flight Control Display Group	Attitude display (2)	

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	Inertial altitude Inertial velocity	Readout counter Readout counter
	Temperature (3)	Vertical columns (3)
	'g'	Vertical meter
	(angle of attack)	Vertical meter
	L/D (lift/drag)	Vertical meter
	Pitch rate	Horizontal meter
	Roll rate	Vertical meter
	Yaw rate	Horizontal meter
Related Instruments (3)	Pressure altitude (2)	Meter
	'q' (2)	Meter
	Standby stability (2)	Meter
Re-entry and Landing Sequence Lights	Mission module separate Drogue chute	Message light Message light
	Main chute	Message light
	Landing probe	Message light
	Retrorocket	Message light
	Main chute release	Message light
Major Systems Status	Information on system operation malfunction	Message lights

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
Attitude Propulsion	Oxidizer	
	temperature	Horizontal meter
	pressure	Horizontal meter
	pounds remaining	Horizontal meter
	Fuel	
	temperature	Horizontal meter
	pressure	Horizontal meter
	pounds remaining	Horizontal meter
	Total on-time remaining	Readout counter
	System 1	
	Roll	Warning lights (4)
	Pitch	Warning lights (2)
	Yaw	Warning lights (2)
	System 2	
	Roll	Warning lights (4)
	Pitch	Warning lights (2)
	Yaw	Warning lights (2)
	Arm	Warning light
	Ready	Warning light
Flap system	Fuel pressure	Vertical meter
	Fuel quantity	Vertical meter
	System pressure	Vertical meter
	Position	
	1 1/2-inch mechanical	Position indicator
	2 1/2-inch mechanical	Position indicator
	3 1/2-inch mechanical	Position indicator

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
Slide projection	Slide projection	Screen
Astro-Inertial Platform Control Group	Star select	Digital readout
	Landmark select	Digital readout
	Azimuth	Digital readout
	Elevation	Digital readout
	Align	Info switch
	Slew	Info switch
	Cage/uncage	Info switch
	Off	Info switch
	Star search/found	Info switch
	Star align/track align	Info switch
	Planet track	Info switch
	CW	Info switch
	CCW	Info switch
	Up	Info switch
	Down	Info switch
Timer	Time to: (3)	Digital readout
	Hours minutes seconds	

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	Elapsed time	
	Hours	Digital readout
	Minutes	Digital readout
	Seconds	Digital readout
	1 Man. Automatic	Digital readout
	2 Man. Automatic	Digital readout
	Warning (3)	Warning light
Seven-inch Scope Display	Diversified information display	7-inch kinescope
Scope Control Panel	No. 1 computer printer (2)	Info switch button
	No. 2 computer printer (2)	Info switch button
	Landing track generator (2)	Info switch button
	Course error pattern (2)	Info switch button
	Periscope camera (2)	Info switch button
	Printer recall (2)	Info switch button
Launch Sequence Lights	1st stage enable	Message light
	1st ignite	Message light
	1st separate	Message light
	2nd ignite	Message light
	Tower separate	Message light
	2nd separate	Message light
	3rd ignite	Message light
	3rd cutoff	Message light
	3rd re-ignite	Message light
	3rd cutoff	Message light

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	3rd separate	Message light
	General cutoff	Message light
Computer control (N/P)	Manual tracker	
	Star	Digital readout
	Landmark	Digital readout
	Occultation	
	Star	Digital readout
	Body latitude	Digital readout
	Time	Digital readout
	Point tracking	
	Star	Digital readout
	Landmark	Digital readout
	Computer address 22	Info switch button
	Off	Info switch button
	Ready	Info switch button
	Standby	Info switch button
	On line	Info switch button
	Transfer store	Info switch button
	Insert	Info switch button
	Verify	Info switch button
	Clear	Info switch button

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
Computer Control Panel (P/c)	Standby	Info switch button
	On line	Info switch button
	Power	Info switch button
	Digital readout	Counter
	Insert	Info switch button
	Verify	Info switch button
	Clear	Info switch button
	Data address (16)	Info switch button (16)
Main Propulsion	O_2	
	Pressure	Horizontal meter
	Temperature	Horizontal meter
	Quantity	Horizontal meter
	H_2	
	Pressure	Horizontal meter
	Temperature	Horizontal meter
	Quantity	Horizontal meter
	Valve pressure	Horizontal meter
	Chamber pressure	Horizontal meter
	Solenoid temperature	Horizontal meter
	Valve failure	Warning light
Miniature Inertial Platform	Align	Info switch button
	Slew	Info switch button
	Cage/uncage	Info switch button

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
Autopilot	Angle of attack	Info switch button
	'g'	Info switch button
	Lift/drag	Info switch button
	Temperature	Info switch button
Message Command Panel	A B C D (4)	Info switch button
	1 2 3 4 5 6 (6)	Info switch button
	Reset (1)	Info switch button
Communications	230-Mc telemetry	
	Receiver 1	Info switch button
	Receiver 2	Info switch button
	Transmitter 1	Info switch button
	Transmitter 2	Info switch button
	Re-entry receiver	Info switch button
	Re-entry transmitter	Info switch button
	Deep space telemetry	
	Receiver 1	Info switch button
	Receiver 2	Info switch button
	Transmitter 1	Info switch button
	Transmitter 2	Info switch button

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	Recovery	
	HF	Info switch button
	VHF	Info switch button
	Beacon	Info switch button
	Both	Info switch button
	PCM	Info switch button
	PDM	Info switch button
	Voice	Info switch button
	Position 1	Info switch button
	Position 2	Info switch button
	All	Info switch button
	External	Info switch button
	Hi-speed low speed	Info switch button
	Recorder 1	Info switch button
	Recorder 2	Info switch button
	Speed level high	Info switch button
	Speed level low	Info switch button
	Record	Info switch button
	Rewind	Info switch button
	Playback	Info switch button

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	S - band beacon	Info switch button
	1	Info switch button
	2	Info switch button
	C - band beacon	Info switch button
	1	Info switch button
	2	Info switch button
	Space antenna	Info switch button
	Slave	Info switch button
	Train	Info switch button
	Erect	Info switch button
	Off	Info switch button
	Azimuth	Dial
	Elevation	Dial
Reactants	Hydrogen:	
	Quantity	Horizontal indicator
	Pressure	Horizontal indicator
	Oxygen	
	Quantity	Horizontal indicator
	Pressure	Horizontal indicator
	Hi-flow (hydrogen)	Message light
	Hi-flow (oxygen)	Message light
	Hi-flow	Message light
	Overtemperature } Fuel cell 1	Message light
	Low Δ P	Message light

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	Hi-flow	Message light
	Overtemperature — Fuel cell 2	Message light
	Low Δ P	Message light
	Hi-flow	Message light
	Overtemperature — Fuel cell 3	Message light
	Low Δ P	Message light
	Temperature	Horizontal meter
	H_2 Δ P	Horizontal meter
	O_2 Δ P	Horizontal meter
	N_2 pressure	Horizontal meter
Cabin Cooling	Pressure	Horizontal meter
	Temperature	Horizontal meter
Electrical Power Panel	Fuel cell 1 - Amps	Horizontal ammeter
	Fuel cell 2 - Amps	Horizontal ammeter
	Fuel cell 3 - Amps	Horizontal ammeter
	Trip 1	Warning light
	Trip 2	Warning light
	Trip 3	Warning light
	External power	Indicator light
	Recovery bus	Indicator light

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
	Mission module	
	Essential bus	Indicator light
	Non-essential bus	Indicator light
	Command Module	
	Essential bus	Indicator light
	Non-essential bus	Indicator light
	Voltage indication	Voltmeter
	Overcharge	Indicator light
	Battery	Indicator light
	Recovery power unit	Indicator light
Environment	COMMAND:	
	Partial pressure CO_2	Vertical meter
	Partial pressure O_2	Vertical meter
	Cabin pressure	Vertical meter
	Temperature	Vertical meter
	N_2 Supply	Vertical meter
	O_2 Supply No. 1	Vertical meter
	Emergency O_2	Vertical meter
	Relative humidity	Vertical meter
	MISSION:	
	Partial pressure CO_2	Vertical meter
	Partial pressure O_2	Vertical meter
	Cabin pressure	Vertical meter

[redacted]

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
Environment - (cont)	Temperature	Vertical meter
	SPACE	
	Radiation:	
	Rate	Digital readouts (5)
	Dose	Digital readouts (5)
	Meteorite impact	
	A	Digital readout
	B	Digital readout
	C	Digital readout
	D	Digital readout
	Solar flare	
	Intensity	Vertical meter (Peak reading)
	Class	
	1	Info switch button
	2	Info switch button
	3	Info switch button
Communications	Output power - watts	Meter
	Modulation level - %	Meter
	Supply voltage - volts	Voltmeter
	Gain control	Meter

TABLE 1-16 (cont)

Operator Display Requirements

System	Part	Type of Display
Navigation Corrections	Angle A	Digital readout
	Angle B	Digital readout
	Angle C	Digital readout
	Δ V	Digital readout
	Time	Digital readout

TABLE 1-17

Operator Control Requirements

System	Part	Type of Control
Attitude Propulsion	Off, System 1, system 2	3-position toggle switch
	Ready, arm	2-position toggle switch
Seven-Inch Scope	Contrast	Rotary knob
	Brightness	Rotary knob
Ten-Inch Scope	Brightness (scope) and OFF	Rotary knob and switch
	Focus (scope)	Rotary knob
	Electrical focus (camera)	Rotary knob
	Optical focus (camera)	Rotary knob
	Azimuth adjustment	Rotary knob
	Elevation adjustment	Rotary knob
Scope Display Control	<u>Seven-inch scope</u>	
	No. 1 computer printer	Push buttons
	No. 2 computer printer	Push buttons
	Landing track generator	Push button
	Course error pattern	Push button
	Periscope camera	Push button
	Printer recall	Push button

[redacted]

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
	Ten-inch scope Same as 7-inch scope	
	For both scopes:	
	Printer recall code	
	Five letter keys (A-E)	Push buttons (5)
	Five number keys (1-5)	Push buttons (5)
Computer Control	On line	Push button
	Standby	Push button
	Ready	Push button
	Off	Push button
	Insert	Push button
	Verify	Push button
	Clear	Push button
	Digital keyboard - 1-10	Push buttons (10)
	Data address (16)	Push buttons
Cabin lighting controls	Selector knob: All, cabin only-emergency	5-position rotary selector knob
	Brightness adjustment	Rotary knob

[redacted]

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Cabin lighting controls (cont)	Transfer store	Push button
	Control selection:	5-position rotary select switch
	Parallel	
	Auto	
	1 Manual	
	Auto	
	2 Manual	
	Program selection:	5-position rotary select switch
	Ascent	
	Midcourse	
	Orbit	
	Re-entry	
	Land	
	Manual tracker:	
	Star	Rotary thumb wheel
	Landmark	Rotary thumb wheel
	Occultation:	
	Star	Rotary thumb wheel
	Body Latitude	Rotary thumb wheel
	Time	Rotary thumb wheel
	Point tracking:	
	Star	Rotary thumb wheel
	Landmark	Rotary thumb wheel
Environmental warning lights	Hold 1 - hold 2 - hold 3	Push buttons (3)
Astro-Inertial	Star select elevation	Rotary thumb wheel
Platform Control	Landmark select	Rotary thumb wheel
	Elevation	Digital readout
	Azimuth	Digital readout

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Platform Control (cont)	Train elevation (up, down)	Push buttons
	Train azimuth (cw, ccw)	Push buttons
	Tracking, off	Push buttons
	Star search, star find	2-position micro switch
	Star search, track align	2-position micro switch
	Planet track	Push button
	Planet track Earth Moon R, L, Off, R, L,	5-position rotary selector knob
	Platform: align	Push button
	Platform: slew	Push button
	Platform: cage, uncage	2-position micro switch
	Azimuth slew	Rotary knob
	Platform slew: slave, automatic, manual	3-position selector knob
	Elevation slew	Rotary knob
Flap System	Off, on, deploy	3-position rotary select knob

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Miniature Inertial Platform Control	Align	Push button
	Slew	Push button
	Cage, uncage	Push button
	Platform slew:	
	Slave, automatic, manual	3-position rotary selection knob
	Elevation slew	Rotary knob
	Azimuth slew	Rotary knob
Main Propulsion	Off: main valve, auxiliary valve	3-position rotary selector knob
Communication Control	230-Mc telemetry	
	Receiver No. 1	Push button
	Receiver No. 2	Push button
	Transmitter No. 1	Push button
	Transmitter No. 2	Push button
	Re-entry	
	Receiver	Push button
	Transmitter	Push button

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Communication Control	Recovery	
	HF	Push button
	VHF	Push button
	Beacon	Push button
	Deep space telemetry	
	Receiver No. 1	Push button
	Receiver No. 2	Push button
	Transmitter No. 1	Push button
	Transmitter No. 2	Push button
	S-band beacon	
	No. 1	Push button
	No. 2	Push button
	C-band beacon	
	No. 1	Push button
	No. 2	Push button
	Space antenna	
	Azimuth	Dial knob
	Elevation	Dial knob
	Slave	Push button

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Communication Control	Train	Push button
	Erect	Push button
	Off	Push button
	<u>Modulation</u>	
	Both	Push button
	PCM	Push button
	PDM	Push button
	Voice	Push button
	Modulation	Rotary thumb wheel
	Volume	Rotary thumb wheel
	<u>Voice intercom</u>	
	Volume	Rotary thumb wheel
	Position 1	Push button
	Position 2	Push button
	All	Push button
	External	Push button

[redacted]

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Communication Control	<u>Recording</u>	
	Recorder No. 1	Push button
	Recorder No. 2	Push button
	Speed level-high	Push button
	Speed level-low	Push button
	Record	Push button
	Rewind	Push button
	Playback	Push button
Automatic Stabilization Control System	ASCS system: on, off	Toggle switch
	Damper: on, off	Toggle switch
	Attitude hold	3-position rotary select
	Automatic sequence Off	
	Roll angle select	Rotary adjust knob
	Angle of attack, hold	Push button
	'g' hold	Push button
	Lift/drag, hold	Push button
	Temperature profile, hold	Push button
	A/P disengage	Switch on hand control
	Pitch adjust	Rotary thumb wheel

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Radar Altimeter Control	<u>On-off</u>	3-position selector knob
	Standby	
	Off	
	On	
	<u>Mode</u>	3-position selector knob
	Moon	
	Earth	
	Beacon	
Slide Projector	Selector	Multiple position rotary selector knob
	Selector	Multiple position rotary selector knob
	On-off	2-position toggle switch
	Focus	Rotary knob
	Select	Push button
Message Command	Four letter selectors	Push buttons (4)
	Six-number selectors	Push buttons (6)
	Reset	Push button

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Standby stability	Off-Re-entry	3-position toggle switch
Lights and Controls	First stage enable	Guarded push button
	First stage separate	D pull ring
	Tower separation	D pull ring
	Second stage separate	D pull ring
	Third stage cut off	D pull ring
	Third stage cut off	D pull ring
	Third separate	D pull ring
	General cut off (abort)	D pull ring
Landing Sequence Lights and Control	Mission module separate	D pull ring
	Drogue chute deploy	D pull ring
	Main chute deploy	D pull ring
	Landing probe	D pull ring
	Retrorocket firing	D pull ring
Abort	Abort handle	Double action handle (commander station) Other stations - electrical

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Timer and Sequence Indicator	Parameter select	Rotary thumb wheel
	Parameter select	Rotary thumb wheel
	Parameter select	Rotary thumb wheel
	Warning signal	
	10 sec	Push button
	60 sec	Push button
	10 min	Push button
	10 sec	Push button
	60 sec	Push button
	10 min	Push button
	10 sec	Push button
	60 sec	Push button
	10 min	Push button
	Select parameter	Selector knob
	Decrease/increase	Toggle switch
	Timer 1	
	Manual/automatic	Toggle switch
	Start	Push button
	Reset	Push button

[redacted]

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Timer and Sequence Indicator	Timer 2	
	Manual/automatic	Toggle switch
	Start	Push button
	Reset	Push button
Reactant Control	Tank selectors	
	H_2 main on-off	2-position toggle switch
	H_2 auxiliary on-off	2-position toggle switch
	O_2 main on-off	2-position toggle switch
	O_2 auxiliary on-off	2-position toggle switch
	Manifold selectors	
	Left and right	2-position toggle switch
	Left and right	2-position toggle switch
	Fuel cell indicator selection (4)	4-position rotary selector switch
	Water separator	
	No. 1, No. 2, off	3-position rotary switch
	Radiator No. 1, No. 2,	2-position rotary switch
	N_2 increase	Push button

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Electric Power	Fuel cell No. 1	
	Off-on low-on high	3-position rotary selector knob
	Fuel cell No. 2	
	Off-on low-on high	3-position rotary selector knob
	Fuel cell No. 3	
	Off-on low-on high	3-position rotary selector knob
	Battery-off, charge-on	3-position rotary selector knob
	Mission bus, off-on	2-position toggle switch
	Command bus, off-on	2-position toggle switch
	Recovery bus, off-on	2-position toggle switch
	Voltmeter selector (7-positions)	7-position rotary selector knob
	Off-fuel cell 1-	
	fuel cell 2-	
	fuel cell 3-	
	battery, c.m.ess-m.m.ess.	
	Voltage regulation	
	Manual-automatic	2-position toggle switch

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Communication System Monitor	Transmitter output Power select	8-position rotary selector knob
	230-mc telemetry-No. 1 and 2	
	DS telemetry, No. 1 and 2	
	Re-entry	
	S-band No. 1 and 2	
	C-band No. 1 and 2	
	Transmitter Modulation Level select	8-position rotary selector knob
	(same as above)	
	Receiver supply Voltage	5-position rotary selector knob
	230-mc telemetry-No. 1 and 2	
	DS telemetry, No. 1 and 2	
	Re-entry	
	Receiver gain control	5-position rotary selector knob
	(same as above)	

TABLE 1-17 (cont)

Operator Control Requirements

System	Part	Type of Control
Correction Data Display	<u>Function selector knob</u>	
	Angle, A-angle, B-angle C- Δ $\vee$ - time	5-position rotary selector knob
	Decrease and increase	3-position toggle switch
	Enable	Push button
Cabin Cooling Control	Selector 1, 2, 3, 4, 5	5-position rotary selector knob
	Command module fans 1, off, 2	3-position rotary selector knob
	Recovery fans on-off	2-position toggle switch

C. DISPLAYS AND CONTROLS

The primary criteria that were utilized in the display system concept were:

(1) Human engineering principles will be applied to the design of the various displays.

(2) Only the information the crew needs to perform their assigned tasks will be displayed.

(3) Information will be displayed to the crew in a form which is compatible with human sensory capabilities.

(4) The various classes of displays, associated with the various categories of information, will be integrated.

(5) As an aid to display integration, the time-sharing of various displays will be considered.

(6) The displays will be arranged in functional locations insofar as possible for each sequential set of tasks.

(7) Sufficient redundant information will be provided to ensure detection and reliability.

The human control or output parameters were considered in terms of:

(1) Effects of accelerative and weightless stress on skilled control performance

(2) Effects of the pressure suit on skilled control performance

(3) Direct manual backups for automatic or semi-automatic control systems when appropriate

The piloting and navigation tasks include many operations where flexibility of subsystem usage is extremely valuable. Accordingly, the display and control configuration incorporates many features of flexibility. These include the capability to control equipment and display equipment outputs in several modes, the ability to switch operational functions from one location to another, the capability of examining data corresponding to future situations and the ability to compare data in groups-both in tabular and analogue form.

Many displays on this vehicle have no requirement for continuous readout. This permits consolidation of the data by printing on paper and since printed data are required for permanent storage, it is convenient to scan these printed data with a television camera system. Certain other data may also be presented by cathode ray tube display with consequent savings in panel space. In addition, certain Pilot-Navigator functions may be redundant with cathode ray tube displays.

The basic categories of displays to be provided to the crew will, in general, consist of vehicular information, environmental information and scientific information. Vehicular information refers to information concerning the status and position of the vehicle itself; environmental information refers to information about the external and internal environment of the vehicle and scientific information refers to data gathered and in some cases transmitted as an integral part of the mission.

1. Description of Displays and Controls

Two display panels in the command module contain the subpanels that accommodate the Apollo requirements for information display and control. Figure 1-III-8 shows the main instrument panel. Contained within the unitized main panel are the following subpanels and units:

(1) Major systems status (warning lights)

(2) Vehicle guidance command

(3) Main propulsion

(4) Attitude propulsion

(5) Flap system display

(6) "q" Meter (2)

(7) Pressure altimeter

(8) Pressure altimeter

(9) Standby stability (2)

(10) Flight control display group (2)

(11) Cabin lighting controls

(12) Sequence lights and controls

(13) Landing sequence lights and controls

(14) Automatic stabilization control system

(15) Printer (alpha-numeric) (2)

(16) Seven-inch scope (2)

(17) 10-inch scope (2)

(18) TV camera (2)

(19) Track generator

(20) Scope display controls (2)

(21) Computer control (2)

(22) Astro-inertial platform control

(23) Miniature inertial platform control

(24) Timer and sequence indicator

(25) Slide projector and controls

(26) Communication control

(27) Message command

(28) Environmental warning lights

(29) Radar altimeter control

The secondary panel contains these elements:

(30) Electrical power

(31) Reactant controls

(32) Cabin cooling control

(33) Communication system monitor

(34) Environment display

(35) Corrections data display

A subpanel to the left of the secondary panel contains circuit breakers, and switches and valves for the environmental system. This subpanel is currently being considered but has not yet been delineated.

The arrangement of the displays and controls on the two-command module panels will be described in detail later in this chapter. Each of the principal subpanels and the associated equipment functions are described.

a. Major systems status (Fig. 1-III-9)

This subpanel contains a series of warning lights which will be arranged according to priority of system information and also will be coded according to color. The prime areas will be allocated to the status of those systems whose malfunction would be critical.

b. Vehicle guidance command (Fig. 1-III-10)

This subpanel contains a grouping of combination light switches identified with vehicle guidance command. The light switch on the left labeled "Normal Control", when lit, indicates that guidance functions are under the astronaut's direct control. At periodic intervals, e.g., one hour, another light identified as the "Automatic Programmer Alert" light will flicker to show that the switch over to automatic programmer control will shortly take place. When this occurs, a vehicle-contained guidance programmer assumes control of such functions as star tracker operations and computer operational functions.. This condition is indicated by the lighting of an "Auto Programmer Control" light. When in automatic command, a switching circuit gives ground-based radio guidance the option of assuming vehicle guidance control, which is indicated by a fourth light. The astronaut will normally determine the mode of vehicle guidance command he desires by engaging the appropriate switch. If he is physically disabled, the system will automatically switch first to automatic programmer and then possibly to ground control.

c. Main propulsion system display (Fig. 1-III-11)

This subpanel displays the condition of the main propulsion system. The pressure, temperature and quantity remaining of both the oxygen and the hydrogen supplies are shown. Valve pressure, chamber pressure and solenoid valve temperature indications are also provided. An off, main valve, auxiliary valve selector knob is provided to activate the system. A red warning light illuminates if the main valve fails to function. The selector knob can then be positioned to switch to the auxiliary valve.

d. Attitude propulsion system (Fig. 1-III-12)

This subpanel indicates the condition and functioning of the reaction jet propulsion system for controlling the attitude of the vehicle. The temperature, pressure and pounds remaining of both the fuel and oxidizer supplies are continuously displayed. A total on-time counter provides an accumulative digital readout for remaining total seconds of use.

Two reaction jet valving systems are used to provide redundancy.

Each system has multiple jets to provide control in the pitch, yaw and roll axes. The failure of each jet valve (from a total of 16 valves) is displayed with a red warning light on the panel. Coordinated with each set of system lights is a toggle switch to permit use of either system. The readiness of each system is checked by means of ready-arm toggle switch. A green light indicates proper functioning, while the red light indicates a malfunction within the system.

e. Flap system display (Fig. 1-III-13)

This display provides information pertaining to the functioning of the hot gas servo power source and the actuation of the aerodynamic control flaps. Fuel pressure, fuel quantity remaining and system pressure parameters are displayed. A three-position selector knob is used to turn on the hot gas system for warmup and then switched to "Deploy" to activate the flap system. Three flap position indicators are provided to indicate successful deployment and proper functioning. The switch-over from reaction jet control to flap system control is accomplished when the flap switch is in the deploy position.

f. "q" Meter (Fig. 1-III-14)

This meter provides information regarding aerodynamic condition which is needed to allow for planning and decision making during re-entry and for abort decisions during launch. The latter information is needed to about five percent accuracy and is presented on a single-turn dial immediately left of the flight control display group.

g. Pressure altimeter (Fig. 1-III-15)

The barometric altimeter is a single-revolution indicator with a range from sea level to 100,000 feet. The dial face will have reference marks at the drogue and main chute deployment altitudes. The expected accuracy requirement of the altimeter is $\pm$ 1000 feet, and it would not be useful for retrograde rocket firing prior to impact because of the high accuracies and the split second timing involved. This altimeter will be useful for:

(1) An accurate indication of pressure altitude during launch and re-entry.

(2) A backup for the altitude-activated sequences; e.g., chute deployment.

(3) A cross check on the altitude readout of the inertial system.

h. Standby stability and angular rate indicator (Fig. 1-III-16)

Prime stability information is combined in one instrument to facilitate controlling the vehicle during emergency or manual operation, and to monitor vehicle performance during automatic operation. Thus angle-of-attack, side-slip and roll angle, integrated into one display, provide an independent indication of this information. Thus, if any emergency situation arises, the display will be available to the pilot in a simplified form, minimizing the possibility of interpretation errors.

During space flight, this indicator is used as a set of meter movements and would be valuable in recovering from tumbling in space flight.

i. Flight control display group (Fig. 1-III-17)

Displays related to vehicle orientation and its relation to basic flight conditions are centrally presented to both pilot and navigator. The flight control instrumentation display group consists of the following:

(1) Flight director-flight reference indicator

(2) Re-entry vertical axis indicator, i.e., "g", angle of attack, lift/drag.

(3) Temperature situation display

(4) Inertial altitude

(5) Inertial velocity

This instrument group is designed to provide adequate information in all phases of the mission and to provide a maximum manual re-entry control capability by means of display centralization and integration.

Flight director-flight reference indicator. This indicator provides information for manual vehicle control or for monitoring of automatic information. An outside-in orientation scheme is used for vehicle orientation for the following reasons:

(1) Multiple reference coordinates are necessary for the Apollo vehicle, i.e., earth vertical, nominal trajectory reference plane, propulsion thrust orientation, reference to celestial bodies and moon and sun reference.

(2) Attitude information is not always primary and it is certain that a one-to-one relationship to earth vertical will usually be undesirable.

(3) The astronaut must be related to vehicle behavior rather than to earth reference.

(4) Human engineeringwise, the indicator is believed to have improved frequency response in the manual mode, few control errors and better zero "g" orientation.

(5) Several equipment developments have been conducted in this particular display concept.

(Hughes FDAI and AVRO ASTRA Indicator)

Flight director "command" needles are provided to aid the pilot in manual modes. Three small axially oriented indicators are provided for displaying additional information.

Re-entry vertical axis indicator. A tape display system will be used to present information related to the prime re-entry parameters. This display provides quantitative indicators for vertical acceleration, "g", flight path angle, γ and lift-to-drag ratio.

Temperature situation display. A tape-type display system is used to depict the thermal management problem encountered in re-entry. The indicator on the left presents, in terms of percent of permissible limit (200°F), the temperature of the internal wall. The center indicator shows, again in terms of percent of the permissible limit (2200°F), the temperature of the metal radiator wall.

The indicator on the right shows in the lower, center and upper portions, respectively (1) the amount of thermal protection material (ablator) already expended (2) the amount of additional ablator material that will be consumed in the remainder of re-entry flight for the re-entry trajectory being examined or flown and (3) an index representing total ablator material available at the start. This indicator is driven by computer-generated data. Inputs to the computer include signals from contact probes embedded in the thermal protective material which measure thickness, and manual computer control inputs which permit trial solutions for the thermal protection management problem.

Inertial velocity. A numeric readout of inertial guidance system velocity will be presented. The latter information is in direct relation to the kinetic energy of the vehicle. This indicator will also be used for displaying the Δ V error during midcourse corrections or injection. A digital readout is used since it provides the quickest possible error-free readout of numerical data known.

Inertial altitude. A numeric readout of inertial altitude will be presented. This information is related to the potential energy during re-entry. The instrument could also be used to display range-to-earth during orbit.

j. Cabin lighting controls (Fig. 1-III-18)

A cabin lighting control panel is provided to permit selection of all, cabin only or emergency lighting modes. Variation in brightness from "off" to "bright" is provided by use of a rotary knob.

k. Sequence lights and controls (Fig. 1-III-19)

Combined launch sequence and warning lights are arranged in chronological order from top to bottom for observation and activation by the navigator-pilot. During normal launch operation each sequence light illuminates (green) and remains on during the event. If an operational event does not occur at its normal time, the sequence light becomes a red warning light. Immediately upon observation of a red light the Navigator-Pilot backs up the event manually by pulling the D ring control. If this manual backup operation successfully causes the event to occur, the red light is extinguished and the green light illuminates. If the manual backup is not successful, the mission must be aborted. At the termination of each individual event, the green light is extinguished. The D rings are spring loaded to return to their original position after activation.

l. Re-entry and landing sequence lights and controls (Fig. 1-III-20)

Six combined landing sequence and warning lights are arranged similarly to the sequence lights. Re-entry--landing event operation and backup is also similar to the launch sequence described.

m. Automatic stabilization control system (Fig. 1-III-21)

This system is designed to provide optimum damping of the spacecraft and to furnish hold and control modes for stabilization and maneuvering. A guarded power switch on the lower left corner energizes the entire system. The damper mode may be singularly selected by the two-position toggle switch immediately above. A rotary selector knob immediately to the right is employed if a constant attitude (Att: Hold), or the preprogrammed automatic flight plan (Auto) is desired. A rotary knob to adjust roll angle for the proper re-entry profile, in accord with the landing pattern, is provided. Small, incremental adjustments in pitch attitude may be performed by means of the vernier wheel along the right edge of the panel (pitch adjustment). Along the bottom are a series of lighted push buttons to select an outer loop mode during the re-entry profile. These outer loops enable the most critical parameter during a particular portion of the re-entry phase (alpha, "g", lift/drag, temperature.) to be held constant during the period when it would be advantageous.

n. Printer (alpha-numeric)

The printer serves as a means of information exchange with computer memory and storage. All manual inputs and certain selected equipment parameters will be permanently recorded on the printer record proper. The printer will be controlled from both the scope display control subpanel and from the computer control panel in conjunction with verification of manual computer inputs. The printer will normally be remotely viewed by kinescope via the four display tubes available. Provision will be made to review the paper record and to use the printer directly in case of failure in the television electronics.

o. Seven-inch scopes (Fig. 1-III-22)

The pilot is supplied with a seven-inch kinescope which functions primarily as a re-entry and landing track indicator which he will use to perform the landing operation. Secondarily, the pilot's kinescope may be used to display the computer data in the event that the navigator is unable to perform his functions. Last and least, the pilot may view the ground situation with a slewable television camera.

The navigator is also supplied with a seven-inch scope that will be used primarily to display the landing track on re-entry. Its secondary usages are to provide computer printer readout and to view the ground via the slewable television camera.

The seven-inch scopes have focus and contrast controls.

p. Ten-inch scopes (Fig. 1-III-23)

A 10-inch cathode ray tube is located directly in front of both the Pilot-Commander and Navigator-Pilot.

One purpose of the 10-inch scope is to display the output of the computer via the TV camera and printer. By manipulating the computer controls in conjunction with the scope display controls, a large variety of guidance and trajectory data, (available either directly from the computer store or by demand computation) is displayed on the 10-inch tube.

Another function of the 10-inch scope is to display a view of the terrain below the vehicle, during landing operations, as seen through a TV camera.

During failure situations the capability exists for displaying data normally presented on the 10-inch scopes on the seven-inch scopes and vice-versa. Further flexibility of display exists in that the data shown on the two 7- and 10-inch scopes may be individually selected by the operator, making it possible to take over functions and aid operations.

The 10-inch scope controls and their functions are listed.

Control	Function
ON-OFF brightness knob	Control power to camera
Azimuth knob	Control rotation of camera
Elevation knob	Control elevation of camera
Electrical focus knob	Vidicon target focus
Optical focus knob	Vidicon Zoomar lens focus
Focus knob	Ten-inch cathode ray tube electrical focus

The scope system block diagram is shown in Fig. 1-III-24. Because of the flexibility and duplication of systems, considerable inherent protection from failure is achieved.

q. Scope display controls (Fig. 1-III-25)

Both the navigator and the pilot have a switching panel that enables them to control the data displayed on the 7- and 10-inch scopes. The panel contains a keyboard comprising letter and number keys that can be used to recall coded printer data for readout. Keys are used to address the appropriate printer and computer, as well as the landing track generator, and camera.

The scope display system is flexible enough so that in the event of a malfunction, all data from any source can be presented on any scope.

r. Track generator

The generation of certain of the displays presented on the 7- and 10-inch scopes requires the availability of a unit that produces specialized deflection voltages. The track generator is such a unit. It is a transistorized package about 4 x 5 x 10 inches which is mounted behind the rear of the forward panel since it does not require viewable surface space. Synchronization and other data signals are supplied by the computer. Control of the track generator output signals to the respective display units is exercised through the scope display control subpanels.

s. Computer control panels (Figs. 1-III-26 and 1-III-27)

Two computer control subpanels are provided. One controls computer No. 1, and the second No. 2 since it is presumed that simultaneous computations are required.

Navigator's panel. This subpanel contains two thumb wheels which supply a readout and computer information input to permit the entry of data from the manual tracker. Similar controls are available for occultation of stars. Point tracking controls are also provided. A bank of 22 labeled push buttons permit insertion of preset programs into the computer. Two five-position rotary knobs control the function according to preset programs when a digital program code is inserted via the 10 digital keys. The keys may also be used to insert new digital data manually. "Insert", "verify" and "clear" push buttons are used in conjunction with the keys. A "power" push button switch turns the computer on. "Ready-wait", "standby-on-line" and "transfer store" buttons permit use of either computer from this panel.

Pilot's panel (Fig. 1-III-27). This subpanel contains a keyboard by means of which various data can be inserted into the computer and the operating modes of the computer can be selected. The "data address" keys are used to address computational problems into the computer and the data is inserted via the numeric keyboard. Before insertion, the data can be verified with the "verify" key. If the correct data appears in the readout window it can be inserted with the "insert" key. If incorrect data appears, the keyboard can be cleared and the data repunched. An illuminated power switch indicates whether the computer is on or off. A "standby-on line" station light indicates whether the computer is ready to accept data (on line station) or whether the operator should stand by pending completion of a computation.

t. Astro-inertial platform control (Fig. 1-III-28)

This panel controls the operation of the platform which consists of a gyro stable platform and a star tracker. (The star tracker may also be used as a horizon scanner.) Slew controls are provided for the platform star tracker as well as the platform itself. Synchro repeaters are provided to permit a visual check of the platform operation.

Indexed star and landmark information is provided by the thumb-wheel roll chart indices which may be set for a particular star and landmark. When this information is set on the chart, it may be utilized to activate the tracker by the switching system. Tracking verification is provided by the combination push button, signal lamp systems.

Additional controls are provided for the inertial platform which is a part of this subpanel.

u. Miniature inertial platform control (Fig. 1-III-29)

The align, auto slew and cage and uncage buttons on this subpanel permit erection and control of the platform. Two manual slew knobs are provided to permit manual slewing of the platform to the drive position. A three-position mode select knob permits selection of the automatic or manual modes, or to a slave mode which slaves the platform to inputs from the computer.

v. Timer and sequence indicator (Fig. 1-III-30)

Elapsed time indicator. The elapsed time indicator will begin counting during the launch countdown at time zero minus 10 seconds and will continue for the entire length of the mission. Three digits are needed for hours. (A 14-day orbital mission equals 336 hours.) Total mission hours are recommended rather than day and hour readout, due to lack of day-night orientation in both orbital and lunar missions. The time of major events can be computed on the ground and learned in terms of hours much more readily than in terms of days and hours.

Time to go. The time until occurrence of the next event is set into one of the three time displays in hours, minutes and seconds. As the time of occurrence approaches, the crew member can directly see the number of hours, minutes or seconds remaining before the event occurs. A 10- 60-second or 10-minute push button warning buzzer is set to provide a signal before the event occurs. All events are listed on tapes for display in the window. To set the proper event name in the window, the serrated wheel is thumbed forward or reversed to display the name of the event.

A timer select switch is provided to permit changing the displayed time in any of the three displays. Time is adjusted by activating the toggle switch labeled "increase", which slews the time readout in seconds, minutes and hours at high speed. Overshoots are reversed by moving the toggle switch to "decrease".

Deflection of the toggle switch from center should be linearly related to the speed of slewing so that a slight deflection will result in a slow slewing change and a large deflection in a rapid slewing change. Activating the "start" button for each display causes the readout to count down to zero. During critical events the duration of the event in minutes and seconds is also displayed as a time-to-go readout.

Timer. Two stop clock timers are provided. These clocks have two main uses:

(1) During navigation fixes, the time between fixes should be accurately recorded. When the location of each fix and the distance between fixes is known, accurate time data are critical in order to determine velocity.

(2) During thrust periods, a readout of the duration of the thrust can serve as a primary information source to indicate accuracy of the correction, since the amount of thrust X duration = total correction made. Thus, if the rocket fires at full force, the duration of the thrust time is the only control for the total thrust desired.

Two toggle switches are required to select a manual or automatic mode for start and stop. For use in navigation fixes, the automatic mode is set to start one switch and to stop the other switch simultaneously. Similarly, when the rocket fires the timer should start, and when the rocket stops, the timer should also stop. For manual control, start and stop push buttons are provided. A reset-to-zero push button is needed for each timer.

w. Slide projector (Fig. 1-III-31)

Various information items are contained on slides and viewed on a projection screen of approximately seven by nine inches. The complete assembly can be mounted on the rear of the screen. A wide-angle screen will be used to present a clear view to both the navigator and the pilot.

The slide projector is used for presenting data such as check lists, star maps, information tables, operating procedures, maintenance procedures, etc.

Being centrally located to men and equipment, rapid access to stored information is available. A method of coding the select controls to allow rapid information selection is a necessary feature.

x. Communication control (Fig. 1-III-32)

This subpanel allows the selection of communication equipment by either the Pilot-Commander or Navigator-Pilot. Push button selection is provided with integral light indication of which equipment is operating and which is malfunctioning. Controls are included for space antenna directional control. Controls are also provided for the type of modulation to be used, level of modulation and receiver volume. Tape recorder, intercom, and beacon selector controls are also furnished.

y. Message command (Fig. 1-III-33)

This subpanel will be used to obtain various coded messages from the computer storage which are then transmitted to earth through the communication system. With the four letters and six numbers, using only one letter and no number for any given message, it is possible to obtain 24 coded messages. It is feasible to obtain more messages by using additional coding symbols.

z. Environment warning lights (Fig. 1-III-34)

These warning lights will illuminate (red) whenever any environmental system malfunctions. An auditory signal to indicate environmental malfunction is also included. (Controls for environmental systems operations are provided on the secondary panel.)

aa. TV camera

The output data from the two printers are picked up by two miniature TV cameras which process the signals for display on the 10-inch, or 7-inch scopes. These cameras are not a part of the viewable surface of the unitized forward panel. The cameras, however, will be mounted so as to be structurally integral with the forward panel.

bb. Radar altimeter control (Fig. 1-III-35)

Switches are provided on this subpanel for "off", and "standby" control, as well as mode select ("earth", "moon", "ready"). A direct numerical readout is provided to register the altimeter output readings prior to computer processing. Controls for elevation and azimuth of the radar altimeter antennas are also included.

cc. Saturn booster monitor (Fig. 1-III-36)

The monitoring of the Saturn booster during launch involves at least three separate areas of display:

(1) The light indicators on the system status panel will show the presence or absence of adequate tank pressures, engine chamber pressures and gimbal system pressure.

(2) The flight reference indicators of the two flight control display groups will show vehicle attitude and angular acceleration.

(3) The 10-inch scopes will display, in analogue or numerical form, information describing the thrust direction of each engine of the Saturn cluster.

dd. Electric power panel (Fig. 1-III-37)

This panel represents the main flow of current in block diagram form. Rotary switches for the three fuel cells are provided. The rotary switch for each fuel cell has three positions: "off", "on low", "on high". To the right of each rotary switch is a corresponding ammeter, one for each fuel cell which is a horizontal type indicator. To the right of each ammeter is a circuit breaker equipped with a status lamp. Next on the right of the warning lights is the fuel cell bus, and above the latter is an amber light which illuminates when external power is being used. The nonessential bus and essential bus for the mission module and the nonessential bus and essential bus for the command module are both supplied by the fuel cell bus. All service busses have status indicator lamps and the nonessential busses may be switched off individually. The recovery bus supplies the essential bus for the command module after separation of the mission module prior to re-entry. The recovery bus which is supplied by the recovery power unit and a battery also has a status lamp. The switch for the battery has three positions: "off", "charge" and "on". To the left of the switch is a warning light for "overcharge".

On the right side of the same panel is a voltmeter with a seven-position rotary selector switch. The seven positions are: "off", 1, 2, 3, "batt", "command module (CM)-essential", "mission module (MM)-essential". Below the selector switch is a two-position toggle switch for "manual" and "automatic" for voltage regulation.

ee. Reactant controls (Fig. 1-III-38)

This panel controls and monitors the status of the three fuel cells. The fuel flow throughout this panel is represented schematically. At the left of the panel four meters indicate the quantity and pressure of O_2 and H_2 in the auxiliary tanks. A group of selector switches to the right of these meters permits selection of fuel flow from either the main tank or the auxiliaries.

Another set of switches permits selection of fuel flow manifolds. Hi-flow warning lamps monitor the manifolds for excessive flow. Fuel proceeds to the three fuel cells, each of which can be turned on or off individually. Each cell is monitored by a group of three warning lamps which signal abnormal conditions of hi-flow, over temperature, or low differential pressure.

To the right of these warning lamps appear a group of four meters controlled by a three-position selector switch. These meters provide measures of temperature and pressures of O_2, H_2, N_2. By use of the selector switch, these variables can be read for the three cells. Adjacent to the N_2 gage, a push button combines a warning light which flashes whenever the N_2 pressure becomes low for any one of the fuel cells. Turning the meter selector switch will reveal which cell is low. The push button is then depressed to raise the N_2 pressure and held until the meter indicates normal pressure again.

At the right of the panel, a horizontal toggle switch permits selection of the left or right radiators and a three position selector switch permits selection of the left or right water separators, the mid-position being an 'off' position for this function.

ff. Cabin cooling (Fig. 1-III-39)

There are two horizontal meter indicators of pressure and temperature. Under each indicator is a five-position rotary selector knob for checking the temperature and pressure in various places in the cooling system. On the right side of the panel are two 2-position toggle switches for the fans. One switch is for command, and one for recovery.

To the right of the meters a three-position knob controls the command module fans during space flight. A toggle switch below this controls power to an auxiliary "recovery" fan powered by the re-entry power system.

gg. Communication system monitor (Fig. 1-III-40)

This subpanel provides quantitative (metered) information pertaining to the power output, modulation level of the transmitters and the supply voltage and gain control for the receivers. There is a rotary selector knob associated with each of the four meters. The two selector knobs used in conjunction with the transmitter meters have nine positions --230 telemetry band, No. 1 and 2; deep space, No. 1 and 2; re-entry; S-band beacons, No. 1 and 2; and C-band beacons, No. 1 and 2. The two selector knobs used with the receiver meters have the following positions: 230 telemetry, No. 1 and 2; deep space, No. 1 and 2; and re-entry.

hh. Environment display (Fig. 1-III-41)

The subpanel is divided into three sections relating to the environment of the command module, the mission module and space, respectively.

The meters for the command module show CO_2 and O_2 partial pressure, cabin pressure, temperature, N_2 supply, O_2 supply -- No. 1 and 2, emergency O_2 and relative humidity. For the mission module, there are vertical meter indications of CO_2 and O_2 partial pressure and cabin pressure and temperature.

The display also presents radiation rate, total radiation accumulation, solar flare intensity, class of the solar flare and indications of meteorite impact.

The meteorite impacts display is a cumulative readout counter, while solar flare intensity is shown by a peak reading vertical meter. The class of flare is shown by three push button lights which are activated automatically by the flare. The light is extinguished by pressing the button which returns the peak reading meter to zero.

ii. Corrections data display (Fig. 1-III-42)

This is a backup display subpanel to provide direct readout of trajectory correction information. The basic function of the panel is two-fold: to provide direct access to vehicle computer generated navigation solutions which would be available even if the forward panel data display equipment failed and to provide direct readout of earth-communicated navigation solutions.

The following five, 4-digit readouts are displayed: (1) Angle A, (2) Angle B, (3) Angle C, (4) $\triangle$ V, (5) Time.

jj. Abort control

A double-action abort handle will be mounted on or near the right hand arm of the pilot's seat. The design and position of the abort control will permit instantaneous operation even when arm movement is constrained.

2. <u>Control Stick Recommendations</u>

The first technique would involve the conventional two-axis control stick with rudder pedals. The majority of available literature on the subject supports this concept. The alternate method utilizes a three-axis control stick. Although less conventional, the practical advantages of this arrangement are also presented for consideration.

a. Two-axis stick plus rudder pedals

<u>Placement and design of control stick.</u> Considerations of high g forces and the necessity of protective restraints for the operator dictate the use of a side-mounted control stick positioned by the right hand of the pilot. The possible

designs of a side-stick controller are almost limitless; of the numerous designs investigated, the pencil-stick appears to incorporate more advantages than any of the others. The principal advantage of the pencil stick is that a minimal decay in performance under high g conditions has been found to develop with this design as compared to more conventional hand-grip arrangements. One reason for this is that the actual control stick is extremely simple and light, presenting almost no dynamic balance problems. Also, the strength-to-weight ratio of the fingers is quite high, permitting precise control of the small pencil stick under considerably higher g forces than is possible with an arrangement requiring movement of the entire arm or forearm. The mechanical output of the pencil stick would be coupled to potentiometers which would impose negligible loading on the arrangement.

Placement and design of rudder controls. The rudder controls recommended are of the full-pedal type with the pivotal axis under the arch of the foot. The pedals themselves are to be the partially enclosed type, covering the front of the foot back to the instep. This configuration has yielded optimal results in centrifuge studies. Placement of the pedals should be under the seat, both to minimize g effects and to get them out of the way for the major portion of the mission when they are not in use.

Linearity of controls. A nonlinear displacement of both stick and pedals is recommended. Experimental results indicate that this principle provides more positive control than does the pure force concept. Of interest is the fact that ground simulator studies often indicate the opposite effect; however, when the same subjects attempt in-flight comparisons between force and displacement principles, displacement configurations invariably receive more favorable support. For the Apollo application, the actual physical displacements of the stick and pedals should be small enough to permit full movement and yet large enough to reduce the effect of inadvertent control inputs due to buffeting or other effects. Plus or minus five degrees in the pitch axis and $\pm$ 10 degrees in the roll and yaw axes are reasonable values for this purpose.

Discussion. The advantages and disadvantages of a two-axis stick with rudder pedals are well defined in the literature and involve both physical and psychological considerations. Cross-coupling between the control axes is minimized by this method. Also, since the individual selected to pilot the Apollo spacecraft will undoubtedly be a trained aircraft pilot, the training period required will be reduced to some extent. Probably the greatest advantage of this arrangement, however, will be in the minimization of negative transfer of training, i.e., the responses required are not in conflict with the earlier training of an aircraft pilot. On the other hand, the rudder pedals are not amenable to the same fine control that could be applied to a three-axis pencil stick under high g conditions, and the added weight and complexity of these additional control elements would appear to obviate many of the advantages of this arrangement.

Specifications. The specific recommendations for the two-axis stick plus rudder pedals are enumerated as follows:

(1) The two-axis stick shall be of pencil-stick configuration, controlling the pitch and roll axes.

(2) The rudder pedals shall be of the differential ankle design, controlling the yaw axis.

(3) All control movements of stick and rudder shall be of the nonlinear displacement-type with a nonlinear force gradient.

(4) The controls shall be electrical with minimum breakout forces and deadspots, commensurate with satisfactory centering and insensitivity to inadvertent control inputs.

(5) The stick shall be located on the controller's right side in alignment with the plane of the right arm and rudder pedals located directly beneath the seat to minimize g effects; proper restraints for both arm and legs shall be employed.

b. Three-axis control stick

The concept of a single control stick incorporating all three axes of control has received considerable attention in recent years. Basically, such a stick is identical to a two-axis stick in providing for pitch and roll control by deflection of the stick in the appropriate directions. In addition, rotation of the stick about its longitudinal axis provides yaw control.

The majority of the studies done with a three-axis stick have indicated poorer performance than is possible with a corresponding two-axis stick. However, these studies employed trained aircraft pilots as subjects and, in view of the element of negative transfer of training, it is felt that the results are not definitive. Since the three-axis stick is logically sound, further exploration is warranted, preferably with subjects who have not been previously trained with conventional aircraft controls.

The most serious criticism of the three-axis stick has been the possibility of cross-coupling effects, (i.e., applications of yaw control reacts upon one of the other axes and vice versa). Several techniques are available for eliminating or minimizing this possibility, such as the use of an enabling switch for the yaw axis, etc. In view of the economics of weight, construction, wiring, etc., to be achieved through elimination of the rudder pedal assembly, coupled with the potentially superior control capabilities of the three-axis pencil stick, it is felt that this type of control should possibly be given serious consideration.

<u>Specification.</u> In general, the specifications applicable to the two-axis stick

also apply to the three-axis stick, with the exception that the control knob would be shaped in the form of the command capsule to enhance its utility. The non-linear displacement of the stick should be similar to the two-axis version, and rotational limits (for yaw control) should be approximately $\pm$ 20°.

Summary. Based on the available data, a two axes electric stick and electric pedals were chosen. Experimental and simulation studies should be conducted to determine the eventual adequacy of a three axes stick.

3. Scientific Mission Controls and Displays

The scientific mission of the Apollo system has not yet been clearly defined. However, as indicated previously, radiation level, solar flares and meteorite impacts, which are being considered under the environmental system, are of scientific interest.

When the scientific mission has been clearly delineated the displays and controls associated with collecting data should allow the operator to:

(1) Rapidly search for areas of interest

(2) Adjust the equipment for intense coverage of a particular signal

(3) Be informed of the suitability of his responses

(4) Be warned as to the existence of unusual signals or activity which require immediate investigation

Due to space limitations, a necessary area of study involves the time-sharing of a number of different scientific instruments by the same display system. The degree of necessary or desirable automation in the collection of scientific information must also be defined.

D. FUNCTIONAL OPERATION OF PRIMARY DISPLAY AND CONTROL EQUIPMENT

The way in which the displays and controls are used is determined by the mission phase. For illustrative purposes, typical operations in several phases of a lunar orbit and landing mission have been selected to demonstrate functional use by the astronauts:

(1) Communications operations	all mission phases
(2) Course correction operations	midcourse
(3) Lunar landing considerations and control	lunar landing
(4) Navigation control	re-entry
(5) Landing control	landing

These operational sequences are described briefly in the discussions which follow:

1. Communications Operations

Up to launch time, the cabin occupants will be connected to the ground crew by the intercom system. In addition, the telemetry systems will be placed in operation to take over the ground communications function during the boost period. Receiver 1 and Transmitter 1 will be operational with System 2 in a standby condition.

The open voice transmission is for emergency communications. Volume controls are used to set intercom levels and receiver output levels. The modulation level is used to set the proper level for the pilot or navigator.

At approximately 1000 miles altitude, the deep space antenna will be erected and Deep Space 1 Receiver turned on. The navigator will then press the track button which will drive the antenna to a position determined by the navigator's reading of computer-provided pointing angles. Upon cessation of the synchro dials (elevation and rotation) motions, he presses the slave button which transfers control of the antenna to the deep space receiver-antenna self-tracking system. The navigator will turn the 230-megacycle telemetry system off at this point to conserve power. Selection of pulse code modulation or pulse duration modulation may be made to permit optimizing the transmission system to the range.

At the point where it is necessary for special data to be transmitted to earth, the navigator may use the communications coded keyboard for standard data formats. Normal data transmission is automatic.

Tape recorder controls are used for recording any or all of the telemetry transmissions. A play-back control is available for the speech recording system.

During the re-entry phase, the telemetry system must be switched back to the 230-megacycle system by the navigator. In addition, the beacons will be reactivated and the navigator will turn on the re-entry communications equipment which will function until recovery is completed.

2. Course Correction--Midcourse

The first requirement in the midcourse correction procedure is the determination of present trajectory of the vehicle with respect to its nominal trajectory. The difference between the two trajectories is shown on a display (Fig. 1-III-43) which would be presented on the seven inch scope by use of the scope display controls.

The top display is an end or cross sectional view of the trajectories. The central index mark indicates the nominal track, while the dot indicates the actual position of the vehicle with respect to the nominal track. The concentric circles are generated from computed data to show:

(1) An inner area (1), such that if the vehicle is here, no correction is necessary.

(2) A shaded area (2), wherein a correction should be made.

(3) An outer area (3), where a correction is not possible and a mission abort is called for.

The lower display indicates the position error along the desired path. The central index indicates the nominal position, while the dot indicates the actual position of the vehicle. Again, Areas 1, 2 and 3 indicate whether correction is not necessary, is necessary, or is impossible.

The steps required by operating personnel for a midcourse correction are:

(1) The seven-inch tube display presents the vehicle's position.

(2) The astronaut notes that the vehicle's position lies within the shaded portions of the displays.

(3) The astronaut refers to appropriate procedures by selecting the midcourse correction slide and views it on the slide projector.

(4) The computer control panel and scope display controls are used to call for trajectory error information to be shown on the 10-inch tube display.

(5) The printer reads out the error information from the navigation computer.

(6) The television camera scans the print-out and presents the data on the 10-inch scope.

(7) The navigator selects the best data if the computer has not previously selected it.

(8) The error data (ΔX , ΔZ , ΔV , etc.) is compared with prestored data to double check if correction is required.

(9) The astronaut enters the error data (including the time of the trajectory information) into the computer control keyboard and requests a correction computation.

(10) The computer provides for three maneuvers:

Time of correction

Δ V

Propulsion direction, in terms of vehicle attitude.

(11) The TV system presents this information on the 10-inch scope.

(12) The astronaut inserts the Maneuver 1 attitude correction values (Δ B, Δ Ø) into the vehicle attitude control system through use of the computer control panel.

(13) The astronaut adjusts the timer and sequence panel for the correct time.

(14) Δ V is inserted through the computer display control panel onto the inertial velocity readout. A decimal shift is required.

(15) X minutes before firing, attitude indicator flight director pointers show B and Ø.

(16) The vehicle is automatically or manually placed in the correct attitude for correction. Flight director pointers become centered when correct attitude is reached.

(17) X seconds before firing, the trigger on the control stick is armed.

(18) Forewarning lights on the attitude indicator and timer-sequencer start blinking during last seconds before firing.

(19) At time zero the astronaut pulls the trigger, which is wired in parallel with automatic firing. Normally, automatic firing leads the astronaut's switch closure by a fraction of a second.

(20) During the firing, the astronaut observes the ΔV error and vehicle attitude in order to make appropriate corrections. When ΔV error goes to zero, the trigger is released.

(21) The astronaut returns displays to the normal mode.

(22) The astronaut inserts Maneuver 2 attitude correction values into the system through the computer control panel.

(23) Steps 13 to 21 are repeated for Maneuver 2.

3. Lunar Landing Considerations

The problem of landing on the moon is similar to the landing on earth (or re-entry) except for the lack of atmosphere. Thus, moon landing can be treated as a problem purely in mechanics without aerodynamic considerations.

For this purpose, it is assumed that the vehicle through midcourse maneuvers has been brought on a trajectory which impacts the moon at the desired location. (It is also possible that a parking orbit might be used before landing.)

The requirements of the landing system are: (1) to reduce the vehicle velocity to zero at impact on the moon surface, (2) to land the vehicle on a certain spot and (3) to land the vehicle in a certain attitude.

This may be accomplished in various manners and the method to be used must be determined as a result of a thorough analysis. Some important considerations in this analysis are: amount of fuel used during the descent, complexity of the control system and possible functions which may be performed by the crew.

The simplest system as far as control is concerned seems to be the use of three independent rocket systems, one for vertical velocity control, one for lateral motion and one for attitude control. This does not necessarily result in the least fuel consumption. Thus, using the same rocket for control of lateral and vertical motion may give better fuel economy. Lateral control is in this case obtained by tilting the rocket axis away from the vehicle velocity vector.

Assuming that the simple arrangement with three independent rocket systems is used, the requirements of the landing system may be listed in more detail as follows:

(1) The attitude control system must keep the retrorocket aligned with the velocity vector.

(2) The retrorocket must start firing at the correct time such that the velocity is zero at landing.

(3) The lateral rocket system moves the vehicle sideways such that landing will take place at a desired spot.

a. Lunar landing control

As the vehicle approaches the moon, the time at which the retrorocket must be fired is computed to give zero velocity at impact. It is assumed that the retrorocket burns until impact. In these computations, a constant thrust level is also assumed. If the rocket thrust level varies and depending on the size of the variation, it may be necessary to use smaller supplementary rockets with on-off control to eliminate the error caused by the variation in the main rocket thrust level.

The attitude of the vehicle is aligned with the velocity vector and held in this mode until landing.

At the computed time, the retrorocket system is fired.

During the first part of the descent, the lateral rocket system is used to keep the vehicle on the desired precomputed path.

Later, when the landing spot can be observed in detail, the lateral system is used to select a proper area for landing. Thus, if closer observation shows that the vehicle is going to land on a cliff, it is necessary to move to a spot which is more suitable for the landing.

b. Crew functions

The results of the studies conducted indicate that the best utilization of man during lunar landing would be in the detection, selection and tracking of the landing point during the last part of the descent.

It was also found that a man can control the path of the vehicle very closely and thus he may be used to hold the vehicle on the precomputed nominal trajectory. The experiments utilized a simulation of moon surface appearance and a landing predictor indication for control. These studies were conducted at Minneapolis-Honeywell.

In the previously mentioned function of selecting and tracking the landing point, the function of the man is of great value. In this case, he cannot be replaced by currently projected equipment.

Under normal conditions, the functions of the crew would be:

(1) To monitor the automatic control system

(2) To select and track the landing spot.

c. Summary of crew functions necessary for lunar landing

(1) Set command signals into the computer to generate the time at which the retrorocket must fire in order that the vertical velocity relative to the moon surface will be zero upon impact.

(2) Enter the computed time into the timer for retro fire.

(3) Enter the landing attitude mode into the attitude control system.

(4) Set the attitude control system in the landing mode (axis of rocket aligned with velocity vector) and give the command to change attitude.

(5) At the correct time fire, or monitor automatic firing, of the retrorocket.

(6) Monitor the automatic control system (error from nominal trajectory, velocity).

(7) Select the landing spot.

(8) Move the vehicle laterally such that landing takes place at the desired spot.

(9) At landing, shut off the retro rocket.

d. Additional remarks

Although in the landing phase the operator is only monitoring the automatic system, he must be able to take over the controls in case of malfunction or failure.

It was mentioned that the operator should select and track the landing spot. Depending on the system used, it may be necessary to see through the retrorocket exhaust flume. Tests indicate that this is possible when certain rocket fuels are used.

The possibility that the vehicle will land in deep shadows must also be considered and lighting might be necessary.

The vehicle sensors must be able to measure altitude very accurately during the last part of the descent. Some form of laser radar may be used giving accurate results even though the beam goes through the exhaust plane.

The constituency of the surface on which the vehicle lands is not presently known. It is possible that if the vehicle lands in a "sea" of loose dust some form of flotation may be necessary to prevent sinking.

After landing, some consideration should be given to the probable high temperature of the moon's surface beneath the vehicle that would be caused by the firing of the retro rockets. Thus, if the crew leaves the vehicle immediately after landing, this area should be avoided. (Bibliography on page 105/106.)

4. Navigation Control--Re-entry

Preparation for re-entry involves these operations by the Pilot-Commander:

(1) Part of the computer and reference system is switched to earth coordinates.

(2) Landing track pattern is displayed on both seven-inch scopes.

(3) The primary landing site is selected from the information displayed on the seven-inch scopes and it is determined whether the landing track and primary landing site is within vehicle maneuvering capability.

(4) If the primary landing site is not within current capability, an alternate landing site is selected (coordination of others stored in computer).

During re-entry these sequences occur:

(1) The Pilot-Commander and Navigator-Pilot observe the earth through the 10-inch scopes with the TV camera aimed toward the ground.

(2) The pilot can select the autopilot mode and instrument parameters needed to carry the flight path to the selected landing area. (re-entry is flown manually).

(3) The pilot switches the 10-inch scope to the critical flight management parameters available for readout in the computer.

(4) The pilot or navigator checks the predicted position based on the stored information and present conditions.

(5) The pilot or navigator receives communication from the ground to check position information.

(6) The pilot's task is to control the vehicle in the current situation and to attempt to reach the selected landing site.

(7) The pilot observes the flight management information, landing track pattern and ground monitor track and predicted landing site so changes can be initiated as soon as possible, when necessary.

(8) The pilot monitors both the 7- and 10-inch scopes as well as temperature, acceleration and other critical re-entry parameters shown in the flight control display group and manually maintains the appropriate vehicle attitude throughout the re-entry phase.

5. Landing Control

Typical usage of the control and display system equipment during landing operations follows.

(1) The pilot observes the landing sequence panel and supplies manual backup as necessary.

(2) When the drogue chute opens at 100,000 feet (or below), the pilot prepares the instruments and controls for use with the landing chute.

(3) The flight director needles are switched to parachute position indicators.

The control stick is switched to scope control.

The TV camera magnification is prepared for ground observation from 15,000 feet to zero.

The navigator receives information from the ground on available wind data regarding velocity and direction. (At this point the actual landing site is known within several miles.)

(4) The pilot controls the parachute flap opening and the vehicle and chute turning to maneuver the vehicle in the indicated direction.

(5) The sequencing system deploys the main landing chute at 15,000 feet.

(6) The pilot observes the terrain through the 10-inch scope (input from TV camera.)

(7) The pilot selects the desired touchdown point based on available wind information, direction and velocity and presence or absence of local obstructions. Wind information is supplied to the computer which provides a predicted impact point. If wind data are not available, the pilot will estimate his predicted landing area. The pilot then selects an available target area which is free from obstructions. Total lateral movement capability must be displayed to the pilot at the 15,000-foot level. This is a circular pattern with the center of the circle representing the present location of the vehicle and the circumference, representing the maximum lateral movement possible.

In a no-wind condition, this circle is displayed around the center of the scope, proportional in size to the magnification selected. A touchdown point can be selected anywhere within the circle. Under wind conditions, the center of the circle will be displaced from the center of the scope proportional to the average direction and velocity of the wind from 15,000 feet to zero, which will act upon the vehicle for the duration of the descent. The area within the circle around this center then will represent the lateral movement capability of the vehicle, taking in account the effect of the wind. A touchdown point can be selected only from within this area.

(8) From the view of the earth on the 10-inch scope, the pilot determines the potential landing area (points that can be reached from present vehicle position under the conditions which prevail, i.e., winds etc.)

(9) The pilot turns the vehicle to the proper heading (by means of vehicle yaw jets) which will ensure the landing of the vehicle in the desired area.

(10) The pilot maintains the best possible vehicle velocity with relation to the relative wind by controlling the flap opening and yaw jet thrust.

(11) When approaching the point of impact, the pilot maintains the vehicle at the attitude which will obtain the slowest lateral velocity at impact.

E. INSTRUMENTATION

Since the feasibility of the recommendations for an Apollo vehicle are directly related to ability to build the required equipment, the life science display-control recommendation has been developed in conjunction with development engineers experienced in display equipment design. This type of cooperation is vital to successfully obtaining early delivery of reliable equipment suited to the job. The Instruments Design Group has reviewed the recommendation and they are discussed here.

Advanced display techniques utilizing electroluminescent materials, solid-state switching and microminiaturization have potential application of great significance in the following areas of Apollo instrumentation:

(1) Status board and warning panels

(2) Numerical readouts

(3) Moving column displays

(4) Meter displays

The foregoing techniques are advocated in the areas listed as a means of improving reliability, minimizing power consumption and providing future growth potential.

Electroluminescent material with its inherent attributes of reliability, low power consumption, multicolor capability and adaptibility of application is logical for Apollo-type display applications. Electroluminescent material brightness and usable life, currently adequate for Apollo application, will measurably benefit from state-of-the-art improvements within the next two years.

Electroluminescent lamp materials may be segmented and arranged in:

(1) A columnar form for a thermometer-type display

(2) A row form for a meter-type display

(3) An ordered matrix form for digital-type displays or simply as an area illuminant

Gating of the electroluminescent lamp excitation voltage, depending on application, may be through techniques of piezoelectric resonance, ferroelectric resonance or conventional solid-state switching. The multicolor capability of electroluminescent phosphors, plus the potential change in chromaticity with variations in excitation frequency, provides the basis for excellent readability based on color contrast as well as brightness differentiation.

1. Microminiaturization

The contemporary state of the art in microminiaturization two years hence will make feasible the application of completely integrated solid-state circuits directly on a suitable semiconductor substrate. This method of packaging will make possible component densities of 3000 parts per cubic inch, exclusive of interconnecting lead wires. Multiple circuits of similar or identical design, such as encountered in an analog-digital matrix, a digital counter and other logical matrices, can be built on a single substrate, including the necessary intraconnections, minimizing the number of input and output lead wires required and, hence, significantly improving total packaging density.

Higher reliability will result from greater knowledge and control of material characteristics and from reduction in the number of connections; package size and weight reduction will result from smaller components, distributed parameter components and integrated single crystal circuits.

Minneapolis Honeywell has suggested five different approaches or types of microminiaturization possibilities:

(1) Type 0--Encapsulated modules fabricated along more or less conventional lines (including welding) from commercially available miniature components.

(2) Type 1--Micromodules. Vacuum-deposited thin-film circuit elements on a mechanically stable base. Transistors are added as "lumps" or built up by deposition.

(3) Type 2--Integrated solid-state circuits. Circuit is built up by etching, depositing or diffusing other materials on a semiconductor basis.

(4) Type 3--Entire circuit is a matrix of deposited material formed by molecular beams played onto a stable base. Concept includes automatic programming for construction of complex three-dimensional distributed elements.

(5) Type X--Molecular electronics. This is the approach of tailoring the molecular structure of materials to perform desired functions, taking advantage of such unconventional circuit possibilities as are illustrated by the solid-state MASER as one example.

It is anticipated that Type 2 and potentially Type 3 microminiaturization will be reduced to contemporary practice within the next two years.

2. Solid-State Switching

Solid-state switching techniques associated with logical matrices, electronic counters, etc., are currently well developed, reduced to practice and are proposed herein. Improvements in techniques and new concepts will undoubtedly occur during the next two years and full advantage will be taken of these anticipated improvements.

The application of solid-state switching techniques to power circuits is justified and proposed only in those areas where improved reliability or other technological needs dictate their inclusion. An analysis of local and remote power load switching frequency and required level of reliability will determine specific applications. For those applications where such a need is present, state-of-the-art components, such as the current silicon-controlled rectifier, are proposed.

3. Status Boards

Utilization of electroluminescent materials in this application could result in a reduction of power consumption up to 10 to 1 over incandescent lamps in the same application. This reduced power consumption with its consequently lowered induced heat load plus the polychromatic capability of electroluminescence makes it a logical contender for Apollo application. Piezoresonant, ferroresonant, or standard solid-state power gating techniques are possible, dependent upon specific end requirements.

4. Numerical Readouts

The utilization of electroluminescent lamp segments to generate numerical data is recommended, based upon reliability, speed of response and low power consumption. Servoed drum-type counters suffer from slow speed, significant power consumption and the reliability limitations of mechanical devices. The disadvantages of servoed counters significantly worsens with an increase in readout range. Electroluminescent readouts are perferred over gaseous glow-type readouts on the basis of reliability and readability. A solid-state display consisting of electroluminescent materials or readout, piezoelectric gating techniques and microminiaturized logic enabling networks presents the possibility of a reliable readout device of minimum size and weight and requires relatively little power when compared to contemporary readout techniques.

5. Moving Column Displays

The replacement of certain servoed vertical tape displays with solid-state moving light column techniques is feasible using the techniques previously discussed. Improved reliability, lower power consumption and reduced size and weight form the basis for the proposed approach. A column of electroluminescent lamp segments are energized sequentially and accumulatively in an upward direction. The excitation power gating and enabling logic could be accomplished by one of the previously discussed techniques (See Fig. 1-III-44).

6. Meter Display

The proposed replacement of moving coil meters by a solid-state readout is based upon considerations of improved reliability and future growth inherent with solid-state devices. Readout is accomplished through utilization of a row of electroluminescent lamp segments. Electroluminescent materials plus suitable power gates and enabling logic suitably packaged utilizing the contemporary techniques of microminiaturization will provide a device of significant growth potential and improved reliability.

7. In-Mission Repair

It is assumed that some degree of in-mission instrument subsystem failure will be inevitable. Also assumed is the accessibility and repairability of the malfunctioning hardware. It is recommended that one goal of the Apollo Instrumentation system design be the optimization of direct interchangeability of subsystems and/or components, to minimize required spare parts, against the potentially undesirable aspects of standardization such as increased cost, weight and imposed functional limitations. It is proposed that all items that are repetitively used such as status boards, warning devices, switches, meter readouts, etc., be directly interchangeable on a component or subassembly basis.

8. Vertical Tape-Type Display

Vertical tape-type servoed displays will be necessary to fill a direct need in Apollo applications where extensive mensuration and display range is mandatory and where an equivalent solid-state display is not practical because of state-of-the-art limitations.

a. Principle of operation

The closed loop self-balancing bridge is employed to obtain maximum accuracy, capability and flexibility of application. The basic indicator or a module of a more complex device consists of a reference bridge circuit, servo-amplifier, servo-motor and tape-drive mechanism and a position feedback transducer.

b. Mechanical features

The tape-drive mechanism is significantly simpler and more reliable than the conventional motor-gear train-capstan drive assemblies.

c. Eccentric drive

The indicator motor and associated speed reduction system are both contained within the tape drive drum of the capstan. Speed reduction ratios of up to 45,000 to 1 are attainable.

An eccentric cam on the two-phase servo motor shaft causes the eccentric gear assembly to mate with the gear teeth at one area on the frame and capstan. The frame internal teeth differ in number from the teeth of the first mesh of the eccentric assembly.

This results in rotation of the gear assembly by action of the motor cam shaft. By proper selection of the quantity of teeth for the eccentric gear assembly, the frame and the capstan, a wide range of reduction rates is achieved.

Accuracy of null balance tape-type displays is dependent on the performance of the tape position transducer. A transducer which is an integral part of the tape eliminates the possibility of backlash between the scale index and the transducer sensing element. Several such transducers have been developed.

d. Tape potentiometer

The tape potentiometer consists of a moving tape with integral potentiometer bobbin imbedded in the tape edge. Resistance values ranging from 200 to 1000 ohms per inch are typical. This arrangement is particularly suited to medium-to-long tapes. Conventional multi-turn potentiometers could also be used in some applications.

e. Linear motion potentiometer

In this instance, the tape carries the collector wiper and the linear potentiometer bobbin is attached to the fixed frame. This construction is optimum for short tapes carrying the display index past a fixed scale. This is functionally equivalent to a conventional single-turn potentiometer which may also be employed.

f. Linear motion synchro tape

This transducer performs the same function as a conventional synchro control transformer, except that the rotor displacement is linear instead of rotational. A two-pole wave winding is applied to the tape which passes through a linear stator consisting of three windings with magnetic axes separated by distances representing 120 degrees of synchro rotation. The error signal induced in the printed rotor provides the position feedback signal for synchro actuated devices. Conventional synchro control transformers are also employed in some applications.

g. Microminiaturization

Reducing microcircuit modules for instrument servo amplifiers and allied circuits results in a significant reduction in weight and volume while materially improving reliability.

9. Flight Director-Flight Reference Indicator

A centrally located flight control indicator will be available for guiding the crew, manual vehicle control or monitoring of automatic operations. This indicator will present a variety of information. Vehicle attitude will be referenced to several different coordinate references: earth and moon vertical, orbit trajectory, the propulsion thrust vector precomputed re-entry trajectory, star and planet orientation. Flight director information will be presented on vertical and horizontal needles. Three small indicators are available for displaying desired parameters such as angular rates.

The display proposed embodies the principle of a moving symbol with respect to a fixed reference (horizon). The vehicle symbol is servopositioned and has full 360 degrees of roll freedom with pitch freedom displayed linearly over the full height of the display. The horizontal and vertical director needles are servopositioned and range over the total area display. It is proposed that the director display be nonlinear, having the least angular deviation per unit displacement at the center of the display and increasing in logarithmetic fashion to the display extremities. The angular rate indicators may be either contemporary galvometers or solid-state meter-type readouts. Choice of readout will be based upon finalized system requirements, input data form and reliability.

A servopositioned flight reference instrument is recommended in lieu of a kinescope display for the following reasons:

(1) Display is to be continuously available, precluding the time-sharing of an existing kinescope system.

(2) Reliability.

(3) Weight, size and power consumption.

(4) Development time and associated costs.

F. PANEL ARRANGEMENT AND CREW STATIONS

The area available for the forward display and control panel and the rear side panel is limited by the internal size of the vehicle and by structural considerations. To some extent, the usable area is further limited to what the operator can see and reach under the restraints imposed by a full pressure suit. These limitations on usable panel space have made it necessary to critically review the need for each display and control. Likewise, the continuing study of the feasibility of combining displays or controls, has been necessary.

Space and position on the display panel were allocated on the basis of priority. Such criteria as frequency of use, importance and function were considered in establishing priority. Where possible, related controls and displays are grouped together to facilitate correlation and comparison of data. The panel arrangement and layout incorporates element locations intended to avoid panel duplication wherever feasible, and instruments and controls were selected to minimize size and weight without functional compromise. Fig. 1-III-45 and 1-III-46 present the panel layout for the command module display and control system as currently planned. The main (forward) panel (Fig. 1-III-45) extends across the full width of the command module and the secondary (rear) panel (Fig. 1-III-46) is located in the right aft section of the module. It will be noted that the particular displays reflect the major crew duties of navigation, control and engineering.

The three duty stations are shown in Fig. 1-III-47. The position on the left side of the main forward panel is that of the Navigator-Pilot, and right is that of the Pilot-Commander. The Engineer-Scientist's position is to the rear and slightly to the right of the Pilot-Commander.

The main panel contains the bulk of the necessary displays and controls. It will be noted that the right and left sections of the panel contain displays and controls that are essentially redundant. For example, the 7- and 10-inch scopes, the flight director, computer controls and indications of g, pressure and standby stability are on both the left and right portions of the panel. The center section of the panel contains such instruments as the slide projector, the timer, the communication controls, the automatic stabilization controls, the controls for the astro-inertial platforms and warning lights indicating major system status. Thus, the men seated at the latter panel (ordinarily the Pilot-Commander and the Navigator-Pilot) can view and control not only their own displays, but those at the center of the panel and to some extent those of the other man.

The secondary panel contains the instruments and associated controls for displaying quantitative information pertaining to environment, communications, reactants, electrical power, cabin cooling and navigation corrections.

The seating and display arrangement described achieves several objectives. One major advantage is that the redundancy of all vital and essential control and guidance functions on the forward control panel permit either the Pilot or the Navigator to assume command responsibility in the performance of any necessary task. That is, all prime vehicular control tasks can be adequately conducted by two crew members, with one-man control being feasible. The capability of achieving vehicle command and control during all mission phases, from either of two operator positions, is important to mission reliability in that such capability makes possible the completion of the mission by one astronaut. In addition, the main control panel concept makes possible task sharing, equipment and data checking operations and continual cross-checking operations between stations.

Another advantage of the present arrangement is the possibility for one man to monitor not only the display and control information presented on the main panel, but also that on the secondary (Engineer-Scientist) panel. Ordinarily, when only one crew member is on duty in the command module, the Navigator-Pilot position will be occupied. By clockwise rotation in the pivotal seat, it is feasible to monitor the secondary panel from the latter position. The possibility for one man to command all display and control information is important for two reasons--the need for a work rest cycle and the need for one man to collect scientific data during certain mission phases. For example, during the moon orbital phase of the mission, it is likely that one man will be sleeping and a second man will be collecting scientific data in the mission module. (However, it should be pointed out that during critical phases of the mission, such as launch or re-entry, all three crew positions will be occupied, and a predetermined division of responsibility will be followed.)

In comparison with the concept of individual control panels for each operator, the design described improves the utilization of available space.

G. DIVISION OF DUTIES

As indicated previously, the three-man crew is tentatively identified as Pilot-Commander, Pilot-Navigator and Engineer-Scientist. The duplicity in vital assignments is intended to reflect flexibility in their capabilities. Although each of these individuals will be specifically selected and trained for his particular specialty to achieve the desired degree of flexibility; cross-training between the various job assignments will also be necessary. In some cases, a certain degree of incompatibility between task assignments may exist, but this factor will vary considerably with the individuals concerned and is almost impossible to analyze in advance of the crew selection.

Based on the requirements of the mission and the display stations, in general terms the division of duties is as follows. The Navigator-Pilot is responsible for monitoring primarily the displays necessary for navigation and secondarily those for vehicle control and system's status. His major responsibilities are conducting guidance equipment verification checks, performing the midcourse guidance fixes, carrying out the midcourse guidance corrections, accomplishing re-entry guidance and checking the injection processes. The Navigator's tasks take place primarily during the translunar, lunar and transearth phases of the mission. During the absence of the Pilot-Commander, or in the event he is incapacitated , the Navigator takes over the latter's functions and authority.

Monitoring the displays related to the control and "piloting" of the vehicle, and to some extent those for navigation and system's status, is the function of the Pilot-Commander. The primary function of the pilot is that of managing mission flight, attitude control in space and aerodynamic control of the vehicle during re-entry and landing. The latter crew member, as commander of the vehicle, makes the abort decision and exercises the abort procedure. The piloting functions are required mainly at various intervals during the trans-lunar, lunar and transearth phases and as indicated during re-entry and landing.

In general, the Engineer-Scientist is responsible for the instruments displaying quantitative information indicating vehicle conditions, subsystem status and crew environment. His functional duties include management of the environmental control system, the electrical tank system and the circuit breaker panel. The Engineer monitors the functioning of the communication system, monitors the radiation dosage warning display, and is the backup monitor of the navigation course correction data. In addition, he performs routine subsystem maintenance and operates the survival and recovery equipment.

One of the other major duties of the Engineer is the operation of the scientific instrumentation and the collection of scientific data. The scientific mission requires the Engineer's attention primarily during lunar orbit and secondarily as the vehicle approaches and leaves the moon. Should an emergency arise, the Engineer assists with navigation and/or vehicle control.

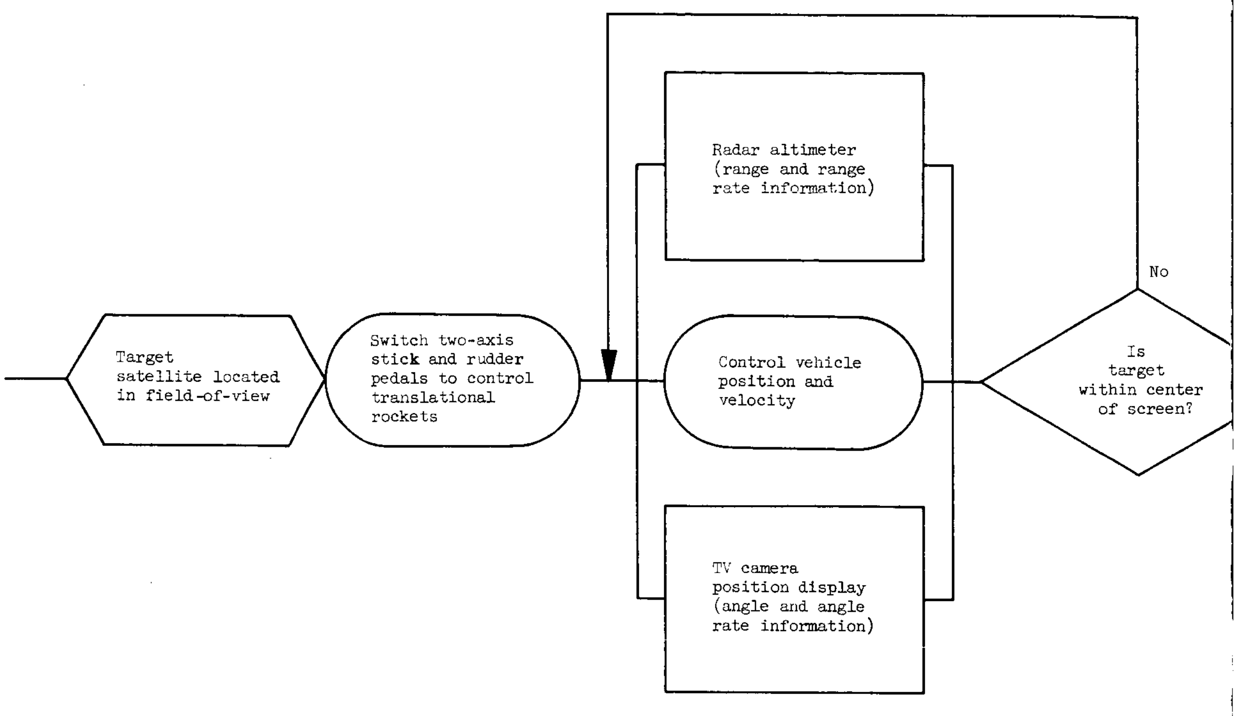
During certain mission phases, e.g., the lunar orbital phase, there will be periods of time during which only one man will be in the command module. The crew member on duty in the latter module will occupy the Navigator-Pilot's position and will monitor all display and control information.

As implied during the course of this discussion, each crew member will have a primary task for which he is responsible in addition, he will also be trained to assume the critical functions of the other two operators.

H. INFORMATION AND COMMUNICATIONS ANALYSIS

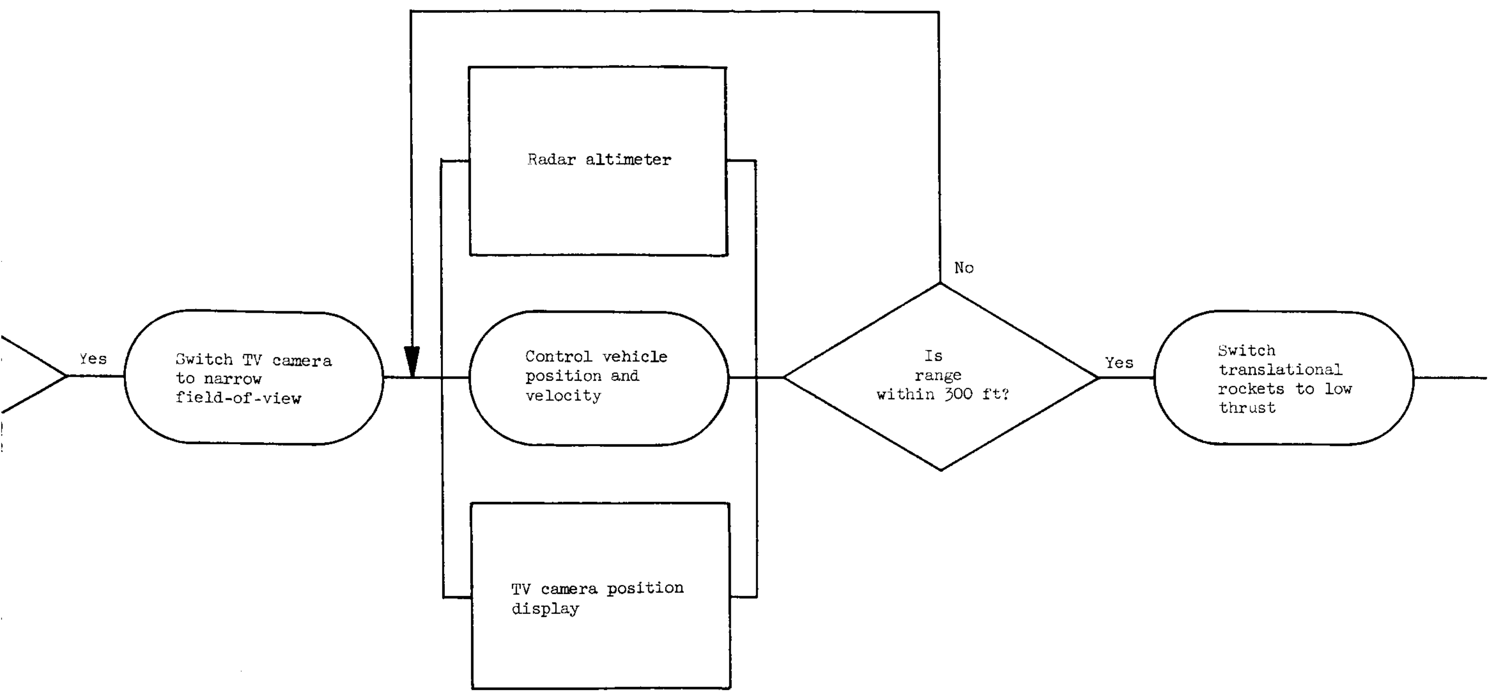
The immediate purpose of this communication link analysis is to enable an evaluation of communication tracks to determine the existence of any possible communication overloading.

Additionally, to do an adequate analysis of this type, the display and control information output must be dissected. As a result, a picture is formed of task delineation which allows rearranging of the displays and/or redistributing of the tasks where necessary to insure optimum performance. There is also an added dividend associated with this detailed look at display panels. It facilitates subsequent communication link analyses of various phases of the Apollo mission other than those discussed here. It is the primary purpose, then, of this analysis to insure the compatibility of panel configuration, task performed, work-rest and communication cycles. The panel design, task analysis and work-rest cycles were each formulated somewhat independently of the others.



Target satellite located in field-of-view
Switch two-axis stick and rudder pedals to control translational rockets
Radar altimeter (range and range rate information)
Control vehicle position and velocity
TV camera position display (angle and angle rate information)
No
Is target within center of screen?

E


Yes
Switch TV camera to narrow field-of-view
Radar altimeter
Control vehicle position and velocity
TV camera position display
No
Is range within 300 ft?
Yes
Switch translational rockets to low thrust

Thus, the link analysis gives the ability to compare these three efforts, and from this comparison conclusions can be drawn concerning the effects of each on the capabilities of man in the operational system.

1. Philosophy of the Link Analysis

Communications will be analyzed in three ways:

(1) between displays and crew members to the extent that this initiates further communication

(2) between crew members

(3) between the vehicle and the ground.

This discussion will include all of the above communications germane to mid-course guidance, re-entry and landing, and will show each communication track via a "link analysis".

These links (Fig. 1-III-49 through 1-III-66) are somewhat stable, although subject to change as panel configuration changes. By stable, it is meant that most changes in displays will not substantially alter communication links. Any alterations in panel configuration are likely to be changes in discrete displays and controls with no gross modification of the information displayed, thus not affecting the communication flow. However, it should be noted that the amount of redundant information greatly decreases the probability of communication between members. Apollo display panels were designed so that all critical displays and controls, other than those located on the Engineer-Scientist's panel, are common or redundant to both the Pilot-Commander and Navigator-Pilot positions.

At this point, it is necessary to state that the communications discussed are not in order of importance. Major emphasis is placed on inter-crew communication with the remaining two types playing a secondary role. The rationale for listing them in this order is one of sequence. To be more precise, those communications elicited by crew members will be a direct result of information output from the displays. Any other communication is assumed to be incidental to the mission.

2. Discussion of Links

a. Delineation of duties

The link analysis performed for this report was done under the assumption that all three members will be on duty, or available for duty, during critical mission phases (launch, midcourse correction and re-entry-landing). This was done to evaluate the necessity of all three members being on duty at these given times.

The link analysis, suggests that only two operators are essential for performance of the tasks involved in mid-course guidance. The Navigator-Pilot must be on duty for the star, earth and moon tracking tasks. The subsequent correction can also be performed from this position. The entire mid-course guidance preparation and correction will take roughly two hours. Although he is not overloaded, this operator must perform a great many sequences in conjunction with the final correction. Implicit in this gross phase are several decisions involving attitude change, initial and final times for correction, nominal paths for correction, not to mention a great many star, earth and moon fixes. Involved in the latter may be the handling of as many as 40 to 50 sets of data for calculation and analysis.

It is then suggested that the old adage, "two heads are better than one" may be apropos. It is believed that the Pilot-Commander should be on duty during this critical phase. It is further suggested that a checkout procedure be formalized to serve as a controlling factor for the elimination of any possible errors.

Consider that each set of data is verbalized aloud by the Navigator-Pilot as he analyzes it. The Pilot-Commander then serves as a checkout observer. Because of the importance of the mid-course correction, it is essential that errors are controlled as much as is feasible and possible.

This designation of duties does not impede the work-rest cycles as much as it might initially appear. Following each mid-course correction there is a period of relative relaxation. Likewise, following each period of sleep there is a two hour "on duty" period with no actual functions performed. Any loss of sleep during the mid-course guidance could be compensated for during the subsequent two hours of "on duty". Thus, the decision to keep three operators on duty during this phase is emphatically supported by the link analysis.

b. Communication links

The major source of normal communication is involved in system checks performed prior to and during the mid-course guidance and prior to and during re-entry; the latter being more prominent. The Engineer-Scientist's station is, consequently, occupied for the purpose of monitoring the system status displays during the operation of these phases.

Communication with the ground occurs only at infrequent times and does not appear to interfere with the normal sequence of events in any way.

It becomes evident from the link analysis that there is very little communication essential to the normal functioning of the phases reported. Most communication is conducted when a malfunction occurs. This is partially due to the redundancy of information. Thus, when an unusual signal appears, it may be reported or pointed out to other crew members. Otherwise, as stated previously, the fact that the front display panel information is either redundant or common to both the Pilot-Commander and Navigator-Pilot, reduces the amount of essential communication.

From the link analysis performed, it appears that with some minor alterations the communication flow and tasks to be performed are compatible with current panel configurations and work-rest cycles.

SUMMARY

The purpose of this discussion is three-fold:

(1) To evaluate the compatibility between tasks performed, displays and work-rest cycles.

(2) To evaluate communication tracks

(3) To evaluate display and control panel configurations.

Communication and information links were analyzed during mid-course guidance, re-entry and landing. Three types of communication are delineated:

(1) From displays

(2) Between operators

(3) With ground.

There is very little essential communication during the normal course of events in the three mission phases analyzed. Most communications will take place only during special situations such as system malfunctions.

In accordance with communication links, the panel configurations and tasks to be performed appear to be compatible. On the succeeding pages are presented the communication link both verbally and diagrammatically. Figure 1-III-48 presents the index used for the diagrammed communication analysis.

MID-COURSE GUIDANCE COMMUNICATION LINKS

1. Request attitude data from computer.

1F Computer displays attitude data.

2. Vehicle is aligned with star reference.

2F Alignment is displayed by three axes indicator.

2.1F Engineer-Scientist monitors fuel.

3. If fuel is critically low, this information is communicated.

4. Automatic star search acquisition routine is turned on.

5. Manual star tracker is sighted toward star no. 1.

5F Feedback is from star and crosshairs.

6. Angular data is entered into computer store.

At this point sequences no. 5, no. 5F and no. 6 are repeated for stars no. 2 and no. 3.

7. Alignment of miniature platform is activated.

7F Activation is monitored.

8. Computer is activated to display automatic and manual tracker readings.

8F These are displayed simultaneously.

9. The tracker readings are monitored and compared.

10. Some communication may take place.

11. Attitude data is requested for earth tracking from the computer.

11F The attitude data is displayed.

12. Vehicle is aligned on three axes.

12F Alignment is displayed on three axes indicator.

12.1 Engineer-Scientist monitors fuel.

13. Manual Tracker is sighted toward earth reference.

13F Feedback from reference point and crosshairs.

14. Angular data is entered into computer store.

At this point, sequences 13, 13F, and 14 are repeated 10-20 times.

15. Computer is activated to display automatic and manual readings.

15F These are displayed simultaneously.

16. These readings are monitored and displayed.

17. Some communications may take place.

This same sequence is performed for moon track with 10-20 repetitions.

18. Request is made for two sets of data from the ground.

18F These are displayed.

19. Based on four sets of data, computer is programmed to determine trajectory errors.

19F These are displayed.

20. There may be some communication on the comparison of readings.

21. The operator has many possible weightings from which to choose. There may be communication on what these should be. He chooses the best of these weightings and compares them with predetermined uncertainty limits. If the data exceeds these limits, a correction must be made.

22. A decision is made on time for initial correction. This may involve some communication.

23. The operator enters the error data, including the time of trajectory information, into the computer and requests a correction computation.

23F Displayed are: Time of final correction, V and propulsion direction in terms of vehicle attitude.

24. Computer readouts are communicated to the Engineer-Scientist for comparison with the correction control panel.

25. The resulting parameters are communicated to the ground.

26. The ground communicates confirmations.

27. The fuel remaining is compared with that required for the correction. Thrust "on" time is checked.

28. There may be some communication concerning this.

29. The operator inserts Maneuver no. 1 attitude correction values (B) into the vehicle attitude control system through use of the computer control panel.

30. Timer and sequence panel are adjusted for the correct time.

31. V is inserted through the computer display control panel onto the inertial velocity read-out. A decimal shift is required.

31F This is displayed.

32. Propulsion and guidance subsystems are monitored.

33. There is a check-out procedure performed.

34. Crew stations are prepared for correction via communication.

35. Attitude is corrected as required.

35F Feedback via three axes indicator and correction control panel.

A delayed feedback is initiated when the forewarning lights on the attitude indicator and timer-sequence start blinking during last seconds before firing.

36. Vehicle attitude is held constant.

36F Monitored on three axes indicator and correction control panel.

37. Engineer-Scientist monitors "time of burning".

38. Engineer-Scientist monitors pressure tank pressure.

39. Engineer-Scientist monitors pressure tank temperature.

40. Engineer-Scientist monitors propellant tank pressure.

41. Any unusual readings are communicated.

42. The operator returns the displays to the normal mode.

43. As a checkout, a new trajectory is confirmed via repetition of correction procedure.

[redacted]

RE-ENTRY COMMUNICATION LINKS

1. At some predetermined time, the re-entry and landing CRT'S are turned on. Unessential equipment is removed from the command module to the mission module and vise-versa.

2. A switch is made from molecular sieve filter to LiOH Filter.

3. The crew members are told to don pressure suits and subsequently that they are in a pressure suit atmosphere.

4. Crew is told to close and seal door to mission module.

5. Engineer-Scientist monitors for any pressure leaks.

6. Landing track pattern is displayed.

7. A decision is made as to whether or not the primary landing site is within current capabilities. Some communication may ensue.

8. Vehicle is aligned to initial re-entry attitude.

8F Feedback from three axes indicator.

9. Modules are detached.

9F This is monitored.

10. Here may ensue some communication.

11. Pilot selects autopilot mode and necessary instrument parameters.

12. Critical flight management parameters are selected.

12F These are displayed.

13. The predicted position is checked against present conditions. Here some communication may be involved.

14. Aerodynamic surfaces are extended.

14F There is feedback via displays.

15. Attitude is controlled for the final time by the rockets.

15F Feedback via three axes indicator.

16. Attitude rockets are turned off.

[redacted]

16F This is monitored.

17. Here there is communication from the ground to check position information.

18. There is possible on-board communication following this.

19. The re-entry flight path is controlled.

19F Feedback via three axes indicator and re-entry CRT.

20. Pilot monitors flight control display.

21. There may be communication if a malfunction should occur.

LANDING COMMUNICATION LINKS

1. Pilot observes landing sequence.

2. Release of drogue chute is monitored through window. If the automatic system does not function, manual over-ride must be used.

2F Feedback.

3. There is possibly some communication.

4. Pilot-Commander prepares instruments and controls for use with main chute. This involves:

    (a) The flight director needles are switched to parachute position indicators.

    (b) The control stick is switched to scope control.

    (c) The TV camera magnification is prepared for ground observation.

5. The altitude pressure is monitored.

6. If this is critical, some communication will take place.

7. The re-entry CRT is turned off.

7F Feedback.

8. Engineer-Scientist constantly monitors the system status.

9. In the event of a malfunction, there will be communication.

10. Available wind data is communicated to the navigator from the ground.

11. The automatic release of the main chute is monitored as in the drogue chute.

11F There is feedback.

12. The Pilot-Commander controls the parachute flap opening and vehicle and chute turning in order to orient the vehicle in the indicated direction.

12F There is feedback from the scopes.

13. The main chute rotation is controlled by the two axes stick and electric yaw pedals.

13F Feedback from the three axes indicator and landing display.

14. Altitude pressure is monitored.

15. With available indications of ground conditions, the Pilot-Commander selects a touchdown point. This may involve some communication.

16. Vehicle is turned to the proper heading via the yaw jets.

16F Feedback via the 7- and 10-inch scopes displaying landing information.

17. Pilot-Commander maintains the best possible vehicle velocity with relation to the relative wind by controlling the flap opening and yaw jet thrust.

17F Feedback.

18. Pilot-Commander maintains the vehicle at the attitude which will obtain the slowest lateral velocity at impact via the two axes control and electric yaw pedals.

18F Feedback from the three axes indicator and landing display.

19. Line is released automatically. The extension of the line is monitored.

20. The retro rockets fire automatically when the line touches ground.

20F Feedback.

21. There may be some communication concerning altitude pressure and and subsystem status. There will be communication preparing the crew for touchdown.

Lunar Landing Bibliography

1. Buckheim, R. W., "Lunar Instrument Carrier-Attitude Stabilization," ASTIA Document No. AD-112402, June 1956

2. Carton, D. S., "Minimum Propulsion For Soft Moon Landing of Instruments," Note No. 94, Granfield College of Aeronautics, July 1959

3. Friedlander, A. L. and Harry, D. P., III, "Requirements of Trajectory Corrective Impulses During the Approach Phase of An Interplanetary Mission," NASA, TN, D-255, January 1960

4. Friedlander, A. L. and Harry, D. P. III, "Exploratory Statistical Analysis of Planet Approach Phase, Guidance Scheme, Using Range, Range-rate and Angular-rate Measurements," NASA, TN, D-268, March 1960

5. Hibbs, A. R., "Exploration of the Moon, the Planets and Interplanetary Space," JPL Report No. 30-1

6. Lang, H. A, "Lunar Instrument Carrier-Landing Factors, "ASTIA Document No. AD-112403, June 1956

7. Peske, A. and Swanlund, G. "Control Considerations for a Lunar Soft Landing," Presented at IAS National Summer Meeting, June 28-July 1, 1960

8. Wheelon, A. D., "An Introduction to Mid-course and Terminal Guidance," STL, GM-TM-0165-00252, June 1958

THE FINAL REPORT of The Martin Company's Apollo design feasibility study comprises the following publications:

System and Operation	ER 12001
Support	ER 12002
Trajectory Analysis	ER 12003
Configuration	ER 12004
Aerodynamics	ER 12017
Mechanical Systems	ER 12005
Aerodynamic Heating	ER 12006
Guidance and Control	ER 12007
Life Sciences	ER 12008
Onboard Propulsion	ER 12009
Structures and Materials	ER 12010
Instrumentation and Communications	ER 12011
Space Environment Factors	ER 12018
Test Program	ER 12012
Fabrication and Quality Assurance	ER 12013
Program Management	ER 12014
Business Plan	ER 12015
Preliminary Specifications	ER 12016